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A Preliminary Design for A Satellite Power System

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Executive Overview

Introduction

This document outlines a preliminary design from Advanced Solar Power Engineering Consultants (ASPEC) for a Solar Power Satellite System (SPS) according to Request For Proposal RFP #SPS-A1-91.

The solar power satellite will provide a clean, reliable source of energy source for mass consumption. The system will use satellites in geostationary orbits around the Earth to capture the sun's energy. The intercepted sunlight will be converted to laser beam energy which can be transmitted to the Earth's surface. Ground systems on the Earth will convert the transmissions from space into electric power. Figure 1 below shows the overall system concept.

The preliminary design for the SPS consists of one satellite in orbit around the Earth transmitting energy to a single ground station. The SPS design uses multi-layer solar cell technology arranged on a 20 km^2 planar array to intercept sunlight and convert it to an electric voltage. Power conditioning devices then send the electricity to a laser, which transmits the power to the surface of the Earth. A ground station will convert the beam into electricity. Typically, a single SPS will supply 5 GW of power to the ground station. Due to the large mass of the SPS, about 41 million kg, construction in space is needed in order to keep the structural mass low. The orbit configuration for this design is to operate a single satellite in geosynchronous orbit (GEO). The GEO orbit allows the system to be positioned above a single receiving station and remain in sunlight 99% of the time.

Construction will take place in low earth orbit and array sections, 20 in total, will be sailed on the solar wind out to the GEO location in 150 days. These individual transportation sections are refered to as solar sailing array panels (SSAPs). The primary truss elements used to support the array are composed of composite tubular members in a pentahedral arrangement. Smart segments consisting of passive and active damping devices will increase the control of dynamic SPS modes.

Project Background

Modern society is based on technology that depends primarily upon burning fossil fuels as an energy source. Unfortunately, dependence on this form of energy has many associated problems. Regional political and religious conflicts can disrupt world wide distribution of fossil fuels which can threaten world stability and peace, as demonstrated by the recent Persian Gulf war. The search for alternative sources of energy has led to the development of solar power. Compared to fossil fuels, the sun promises to be an infinite source of energy. Technology has already created the ability to harness the power of the sun cheaply and efficiently without the drawbacks of fossil fuels. This study builds upon the concept formulated in 1968 by Peter Glaser and on research conducted in the late 1970s on Satellite Power Systems. ASPEC's objectives are to make an integrated satellite design and to update previous findings with the application of modern technologies.

System Guidelines

Guidelines for the Satellite Power System design have been established by the RFP in the form of assumptions and requirements. The following are selected assumptions used to guide system development:

1. Technology available by the year 2000.
2. Cost is not a design parameter.
3. Launch failure rate is 1%.
4. Weight growth factor of 15% should be reflected in final mass estimates.

The following are basic system requirements established by the Request For Proposal:

1. The SPS will supply 5 GW to a ground site.
2. Damage to Earth and space environment is minimal
3. Space debris from construction/operation is minimal
4. System life is 30 years.

Solar Technology

The selection of a solar to electrical energy conversion method is a primary consideration in realizing the SPS concept. This study researched the two methods of energy conversion considered to be feasible for use by the year 2000, solar dynamic systems and solar photovoltaic cells. After completing research on these two types of energy conversion methods, solar photovoltaic cells were selected for use on the SPS. This selection was based upon a comparison of the relative advantages and disadvantages of the two conversion methods.

ASPEC proposes to reduce the costs of the solar array by using plastic lenses to concentrate sunlight onto small-area single crystals. The concentrator lens/solar cell approach has additional advantages over single crystal units. Since the cells are small and located behind lightweight optics, they can be shielded easily for improved radiation resistance leading to higher end-of-mission performance. Also, the use of smaller size solar cells leads to higher manufacturing yields. As Figure 5 shows, assuming one defect per wafer, the material utilization is 90% in the small concentrator cell approach, as opposed to 64% for large flat plate solar cells. Lightweight, plastic Frensel lenses have been chosen for the SPS design. In addition to their low weight, the lenses can be manufactured easily and inexpensively in mass quantities [3:286-289].

In the last decade, solar cells have consisted of a single layer of material converting a specific range of the solar spectrum to electricity. Efficiencies as high as 24% in the space environment have been recorded using this approach. Recent breakthroughs in solar technology have led to the development of double and triple layer cells. Current work with two layer tandem cells has produced cells achieving efficiencies as high as 31% [1:299]. Predictions have been made for three layer tandem cells with conversion efficiencies of 48.6%. Such highly efficient cells are ideally suited for the SPS, resulting in a reduction of the number of cells and the size of array panels needed to produce 5 GW.

The Solar Technology subgroup conducted research to select the appropriate materials for each layer of the stacked cell. Current research indicated GaAs and AlGaAs as prime candidates for the top layer. Silicon, GaSb, or InP are possibilities for the second layer. The most work remains to be completed in the manufacturing of the third layer. By the year 2000, based upon trends in solar technology, the major candidate for the bottom layer is InGaAsP [2:190-194].

In developing efficient multi-layer solar cells, each layer must be made transparent to certain frequencies of light used in the lower cells. To accomplish this, the solid metal backing normally used to collect and conduct the current on conventional cells is eliminated. In its place is a grid of fine metal lines on the top of the cell that perform the same function [1:299].

The concept of a multiple stack concentrator cell is demonstrated in Figure 7. The concentrating lens is fixed above the stack (typically at a height of 1"). Light passes through the lens and is focused onto the smaller cell assembly where it first strikes a prismatic Entech cover. This cover bends the light around the metal gridlines on the surface of the solar cell.

Orbits & Controls

Control of the SPS is accomplished by integrating the components used on SSAPs into a complete system once at the GEO station. The SSAPs (solar sailing array panels) will be assembled at a space factory in low Earth orbit (LEO). All of the materials required for this will be sent up to LEO with a heavy lift launch vehicle (HLLV). This could be accomplished with a smaller vehicle, but even with a HLLV that can carry 2.5 x10^5 kg to LEO, this will take at least 165 launches.

Each SSAP will consist of a 1 square kilometer section of the solar array, four gimbaled ion thrusters, two cylindrical pressure vessels that each contain 77200 kg of Argon, and an attitude reference determination system (ARDS). The ARDS consists of a CCD (charged coupled device) sun sensor, two CCD star sensors, a set of three rate gyros, and a processor that will interpret the sensor readings and control the thrusters. The total mass of each SSAP is 2.055 x 10^6 kg.

After the SSAP is assembled, it will spiral out with a constant tangential, low thrust to geostationary Earth orbit (GEO) where the fully assembled SPS will be. The SSAP will power itself with its solar array which will remain perpendicular to the Sun's rays. The SSAP will also have batteries for power during shadow. The transfer will be powered by four ion engines, with an first approximation calculation making the resulting thrust be tangential to the transfer path. The total time of this transfer is approximately 150 days.

Once the SSAPs arrive at GEO, they will be integrated into the SPS. This will be done by telerobotics. The thrusters and ARDS will be removed from each of the SSAPs and the SSAPs will be joined together to form the SPS. The thrusters will be attached to the corners of the SPS (20 at each corner), one pair of ARDSs will be located at each corner of the SPS, one pair will be located at the center of mass of the SPS, and one pair will be located on each side of the transmission dish. The processors will be removed from the remaining six ARDSs and evenly spaced along the SPS array and converted to monitor damage. The leftover sensor and gyros will be stored with the robots in case they are needed later as replacement parts. The final configuration of the SPS is shown in Figure 13.

The thruster system features an argon ion bombardment thruster reaction control system operating an average of 36 thrusters at a time. Each thruster is an Argon ion bombardment thruster with a specific impulse of 13,000 seconds and a thrust of 23 Newtons. They require 1275 kW of power,and a one meter aperture. The thruster system will be controlled by the attitude control computer. The attitude control computer will receive its information for the processors from each of the ARDSs.

Power Transmission

The Power Transmission subsystem studies selected a CO_2 laser based subsystem. Laser and microwave were compared based on five different criteria: size of transmission optics, efficiency, flexibility of system, development of technology, and area of ground station required.

Size of transmission optics was considered the most important criteria. Depending on the type of laser chosen, the transmitting antenna will be 10m to 60m in diameter and weigh from 10,000 kg to 100,000 kg [8:F-1,F-2]. The next criteria is electric to beam conversion efficiency. Laser conversion is estimated to have significantly lower efficiency (30% to 80%, depending on the type of laser) than microwave conversion (80% to 90%) [8:40]. This is the only area where the laser concept falls below that of the microwave. Flexibility of the system is incorporated into future possible operating scenarios. Since the laser beam is small, it could be employed for aircraft propulsion or to provide power for spacecraft or space stations. The development of laser technology is behind that of microwave but research is continuing to advanced laser capabilities especially in SDIO studies. Finally, the area of the ground station is a relatively minor criteria, due to the fact that the cost of purchasing real estate may be considered negligible when compared to the other costs of this project. The amount of area required for a ground station to receive a laser beam (about 200 acres) is much smaller than the area required to receive a microwave beam (about 80,000 acres) [8:G-1]. After considering and weighing the previously described criteria, ASPEC chose laser as the best mode of power transmission for the SPS.

The Laser Power Transmission Subsystem (LPTS) will consist of four major elements: Electrical Power Supply, the Closed Cycle Laser, Heat Removal, and Optics. These elements are detailed in the following section. A side view of the LPTS is shown in Figure 13.

The LPTS will require some power conditioning of electricity that is produced by the solar arrays. This power conditioning is needed to convert lower voltage solar cell power into high voltage power for laser pumping. This can be done at an efficiency of 95% or higher [10:710].

Four types of lasers considered were the Carbon Dioxide Laser, Carbon Monoxide Laser, Iodine Solar Pumped Laser, and Semi-conductor Diode Lasers. The first electrically driven laser developed was the Carbon Dioxide (CO_2) laser. It has a wavelength of 10.6 micrometers. For a geosynchronous satellite at about 40000 kilometer range, it will require a 60 meter diameter aperture to beam to a 10 meter diameter spot on the ground. As of 1989, the CO_2 laser is the most developed high power gas laser and promises an open cycle efficiency of greater than 60% operating at 409 Kelvin [10:711].

The heat removal element of the LPTS consists primarily of radiators. If we assume our CO_2 laser can operate at 80% efficiency, then 1.316 GW will be absorbed by the lasant and must be removed continuously to maintain the lasant at operating temperature. This task will be performed by radiators nearly 1.22 square kilometers in area. The radiators will be located near the transmission end of the SPS, underneath the solar arrays, as as shown in Figure 13, in order to protect the radiators from heating and solar degradation [13:31].

An adaptive optical system employing active controls to remove beam aberration aims and focuses the laser radiation. The transmitting aperture expands the narrow beam from the laser device and corrects for any beam distortion. A Cassegrain aperture configuration using a large concave primary mirror and a small convex secondary mirror is employed. The primary mirror surface is composed of small mirror plates supported by five actuators on a reaction structure supported an a truss structure by coarse actuators. The combustion of these actuators and mirror segments conforms the primary mirror to the desired shape [9:78].

Safety

There are many safety concerns associated with beaming lasers to earth. The primary concern is the effect laser beams might have on humans in the vicinity of the reception site. This problem is avoided by locating the receiving site in an area of sparse population and building a fenced buffer zone around the target area. Another safety concern is whether airplanes will be able to fly through this beam. A radiation level as high as 1.5 W/cm^2 is permitted for aircraft, but our system will beam as much as 10 w/cm^2 to the ground. Thus, we will have to restrict airplane flight in the vicinity of the beam [8:50].

Environmental Concerns

The primary environmental effect of beaming lasers to earth is the effect the wasted heat (energy at the ground station not converted to electricity) may have on the climate. It has been found that this atmospheric phenomena occurs only in a confined area of 200 acres around the receiving site thus, the global or regional climates will not be affected [8:49] Secondly, animals, primarily birds, will be protected by controlling the beam intensity. This is done in such a manner that an inner, high power beam is surrounded by a lower power ring region in which birds will be able to sense the increase in temperature and will desire to fly away from the central beam. Also, placement of the receiving station will take into consideration the migratory flyways and be located at an acceptable distance away.

Rain clouds also present a problem. The inability of laser beams to penetrate rain clouds reduces their overall operating efficiency drastically. This problem may be addressed by locating the ground site in an area that has a maximum number of clear days in a year, placing the site high enough so that most of the weather phenomenon is below, or by using special beaming techniques such as laser hole boring.

Sociopolitical and International Concerns

A laser beam from outer space beaming large amounts of power may be a threatening proposition to people living near a ground station. People living near a ground station may be more inclined to accept the SPS if they learn of the economic benefits to their community that the SPS might have, like providing more jobs and increasing economic activity in the area.

There may also be international concerns of whether a laser system can be turned into a weapon and used for military purposes. Since any decision to use this system as a weapon will have to be deliberate and premeditated, these concerns can be somewhat remedied by making SPS subject to full disclosure and public, and even international, participation.

Structures

With a required solar array area on the order of 20 square kilometers (about seven square miles), the SPS will be by far the largest man made structure ever placed in orbit. The supporting truss structure is required to support the cell arrays, support the subsystems, and give accuracy to the pointing of the arrays. Three types of truss were considered: Tetrahedral, A-Frame, and Pentahedral. The Pentahedral truss combines ease of serviceability and load handling efficiency. This design contains no tension members while allowing access to the square sub arrays which easily lend themselves to modular design. As a result of these advantages, the pentahedral truss was chosen to be the primary supporting structure for the SPS.

Materials

The choice of materials is another important consideration in the design of the SPS structure. Availability, low manufacturing costs, and a large amount of existing performance data make conventional alloys primary candidates for use as materials for structural members. Aluminium alloys feature a high stiffness to density ratio and excellent workability and a low level of magnetism.

Unfortunately, Aluminiums low yield strength may be prohibitive [13:209]. Composites combine high strength, extremely light weight, low thermal conductivity, and tailorable elastic properties making them another worthy candidate for use as structural member materials. Effective oxidation coatings are essential, however, because even slight damage to the surface (which may be ignored with conventional alloys) can destroy the integrity of the composite fibers, resulting in a catastrophic failure. In addition to the special coating, electrical grounding must be achieved by using conductive strips located throughout the structure. As a result of these drawbacks, composites have been previously relegated to roles as secondary structures [13:211]. New developments in the field, however, are occurring at a rapid pace, and it is thus not unreasonable to expect that solutions to such problems may be found in the very near future [15:35-38].

As a result of these projected developments, composites have been chosen as the primary material for the SPS truss structure. Specifically the material data for Du Pont Kevlar 49 was used in all structural calculations.

Smart Structures

The large, flexible supporting structure required by the SPS will require an advanced structural control system. Active structural elements will be able to independently vary their damping coefficients, will be dispersed throughout the structure where they will automatically respond to minimize any damaging effects. Active members using electro-rheological (ER) fluids as a stiffening mechanism show particular promise [17:17-21]. ER fluids possess the unique property of a viscosity that varies with an applied electric field. As a result, a nearly immediate increase in damping to respond to structural perturbations is possible. Besides controlling the damping electronically, a structural increase in damping can be accomplished by using an elastomer between layers in the composite tubes. The inner and outer tubes can then shear independently and excess energy is absorbed in the elastic layer. Figure 20 shows the composite tubing with the elastomer layer.

Modular Construction

Due to the sheer size of the SPS, it is not feasible to attempt to assemble the entire satellite in LEO and then transport it to GEO. Thus, the structure must be designed with some degree of modularity. The SPS will be constructed from a number of individual solar sailing array panels (SSAPs). The SSAPs are in turn composed of smaller individual solar panels. These panels will also be incorporated into individual modules containing their own lenses, solar cells, and rigid backing structures. Thus, the solar panels are designed to be easily removed and replaced. Construction of the SPS will take too long and be far too dangerous to make human assembly feasible. Thus, most of the assembly tasks will be performed robotically.

Launches from Earth will primarily carry pre-processed materials into LEO where an orbiting "space factory" will extrude the tubular members and assemble the truss structures. This eliminates the need for a collapsible structure designed to fit inside the payload bay of a launch vehicle. Prototype remote facilities for manufacturing structural members and constructing truss structures like the Grumman beam builder shown in Figure 22 have already been built and tested.

The primary steps in assembly of the SPS are as follows:

1. Establish a "space factory" in LEO with facilities to manufacture the structural elements and assemble the SSAPs.
2. The pre-processed structural materials will be launched for manufacture of structural elements. The solar panels will be manufactured on Earth and launched for assembly in LEO.
3. The truss structure will be assembled from its individual elements and solar panels will be mounted

until an entire SSAP is produced.

4. The SSAP will be transported to GEO using ion thrusters powered electricity generated by the SSAP itself.
5. Final assembly will occur in GEO as robots assemble the arriving SSAPs to form the operational SPS.

Robotic Maintenance

Robots will be used extensively to perform both routine maintenance and unscheduled repairs of the SPS. The robotic maintenance system will be primarily composed of two robots mounted railing fixed to the SPS. As shown in Figure 23, the mounting rail will move the robots over the length of the SPS, while the robots themselves will move transversely along the rail. This system, which operates much like an ordinary computer plotter, allows any point on the SPS to be easily reached. These rail mounted robots will be primarily used to perform routine repairs, especially replacement of damaged solar cells. The mounting rails will extent around the edge of the SPS to allow the robots to service the rear of the structure. Direct human involvement will only be required if a problem arises that is too complex to be handled entirely by the robots.

Computers

The on-board computer system for the SPS will be comprised of a network of five computers. A master control computer, tied to ground control via a communications link, will oversee the operations of a thermal supervisory computer, power distribution computer, attitude control computer, and a laser transmission computer [19:4-35].

Over the lifetime of the SPS, power output from the solar arrays will decrease due to damage from solar/cosmic radiation and space debris impact. The power distribution computer will monitor power output to provide ground control with the location of highly damaged array modules. Furthermore, because SPS power requirements will be different when the satellite is in shadow, the power distribution computer will also serve as a power manager by shutting down unnecessary systems during shadow times and restarting them after the system passes out of shadow.

Communication

Communications link the ground, robots, and subsystems of the SPS together. Currently, a high frequency pointing link will be used to assure the accurate pointing of the laser beam. Ground commands will be carried via TDRSS during assembly and a local ground station during the operational lifetime. Robotic assembly scenarios considered to date require that the robots be primarily autonomous, with telerobotic capabilities for specific / rare jobs that require this feature.

System Problem Scenarios

Several possible worst case scenarios and possible solutions are outlined below.

Worst Case Scenario	Solution
SPS becomes controlled by destructive organization/person	Critical self destruct activation
Fail-safe mode for transmission pointing fails	Critical self destruct activation
SPS suffers massive damage from a meteor shower	Robots remove least damaged panels and move to start-up configuration locations
Loss of attitude/reaction control and SPS begins to tumble	Release tethered thruster modules to despin SPS
Catastrophic failure of a major subsystem	Send up more parts from LEO

Note: Critical self destruct does not actually destroy SPS, it merely becomes inoperable.

Table of Contents

Table of Contents

List of Figures

List of Tables

1.0 General Summary

This document outlines a preliminary design from Advanced Solar Power Engineering Consultants (ASPEC) for a Solar Power Satellite System (SPS) according to Request For Proposal RFP #SPS-A1-91. This report is divided into five main sections: general summary, technical designs, management, references, and a bibliography.

1.1 Project Background

Modern society is based on technology that depends primarily upon burning fossil fuels as an energy source. Unfortunately, dependence on this form of energy has many associated problems. Regional political and religious conflicts can disrupt world wide distribution of fossil fuels which can threaten world stability and peace, as demonstrated by the recent Persian Gulf war. Also, the burning of fossil fuels leads to another problem, pollution of the earth environment. Fossil fuels are being linked to the effects of global warming, acid rain, and health risks from breathing polluted air. Another problem associated with dependance on this form of energy is that fossil fuels are a limited resource, and consequently, there is a continuing search for alternative energy sources.

The search for alternative sources of energy has led to the development of solar power. Compared to fossil fuels, the sun promises to be an infinite source of energy. Technology has already created the ability to harness the power of the sun cheaply and efficiently without the drawbacks of fossil fuels. This study will build on the concept formulated in 1968 by Peter Glaser and on research conducted in the late 1970s on Satellite Power Systems. ASPEC's goal is to make an innovative design and update previous findings with modern technology.

1.2 Project Objective

The objective of this project is to design and develop a satellite system that will gather the sun's energy in orbit to produce electricity on Earth. This effort includes investigation of the technical, economic, and environmental considerations of the SPS. ASPEC will deliver a final report describing the design of the system along with a poster and model depicting the design.

2.0 Technical Designs

The technical design areas provide a general design for a satellite power system. In addition, alternate concepts for several aspects of the proposed SPS design are given. The tasks required further in each area to successfully complete the project are also detailed.

2.1 System Guidelines

Guidelines for the Satellite Power System design have been established by the RFP in the form of assumptions and requirements. The following are assumptions used to guide system development:

1. Technology available by the year 2000.
2. Cost is not a design parameter.
3. Launch failure rate is 1%.
4. Weight growth factor of 15% should be reflected in final mass estimates.

The following are basic system requirements established by the Request For Proposal:

1. The SPS will supply 5 GW to a ground site.
2. Damage to Earth and space environment is minimal
3. Space debris from construction/operation is minimal
4. System life is 30 years.

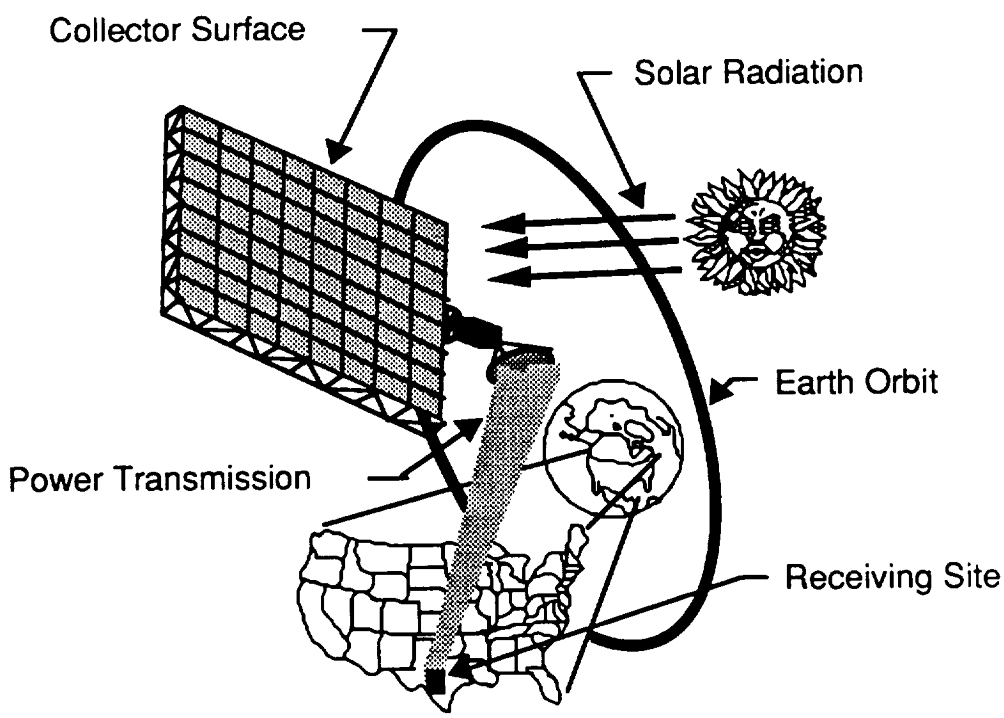


Figure 1. Overall System Concept

2.2 Conceptual Overview

The solar power satellite will provide a clean, reliable source of energy source for mass consumption. The system will use satellites in geostationary orbits around the Earth to capture the sun's energy. The intercepted sunlight will be converted to laser beam energy which can be transmitted to the Earth's surface. Ground systems on the Earth will convert the transmissions from space into electric power. Figure 1 shows the overall system concept.

Preliminary Design: SOLAR CELL-LASER-GEO

This preliminary design for the SPS consists of one satellite in orbit around the Earth transmitting energy to a single ground station. This SPS design uses the latest solar cell technology in a large planar array to intercept sunlight and convert it to an electric voltage. A device then converts the electricity to a laser beam, which is then transmitted to the surface of the Earth. A ground station will convert the beam into electricity. The orbit selection for this design is to operate a single satellite in geosynchronous orbit (GEO). The GEO orbit allows the system to be positioned above a single receiving station and remain in sunlight 99% of the time.

2.3 Procedures and Tasks

The following eight sections describe the major subsystems as defined by ASPEC. Each subsystem area covers the progress made to date and future work to be accomplished.

2.3.1 Solar Technology

The selection of a solar to electrical energy conversion method is a primary consideration in realizing the SPS concept. The solar energy conversion subsystem comprises a significant portion of the total mass and cost of the satellite. In addition to these two factors, manufacture, transportation, and construction of the subsystem are also important considerations in selecting the energy conversion method. This study researched the two methods of energy conversion considered to be feasible for use by the year 2000, solar dynamic systems and solar photovoltaic cells.

Solar Dynamic Systems

Solar dynamic energy conversion methods use concentrated sunlight to heat a working fluid which drives a thermodynamic engine (see Figure 2). The sunlight is concentrated by a parabolic mirror onto a cavity containing the working fluid. The heated fluid is then used to drive a conventional thermodynamic engine such as a Brayton cycle and/or Rankine cycle engine (see Figure 3). Solar dynamic systems possess a number of advantages such as their:

- high conversion efficiencies
- relatively small collector/concentrator areas
- large scale power production capabilities

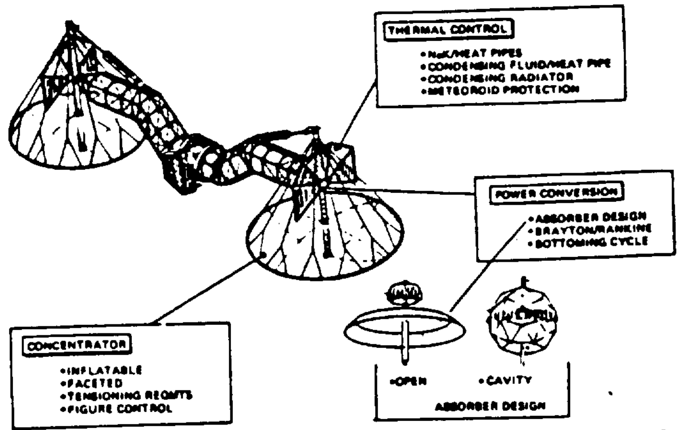


Figure 2. Solar Dynamic System Concept for SPS

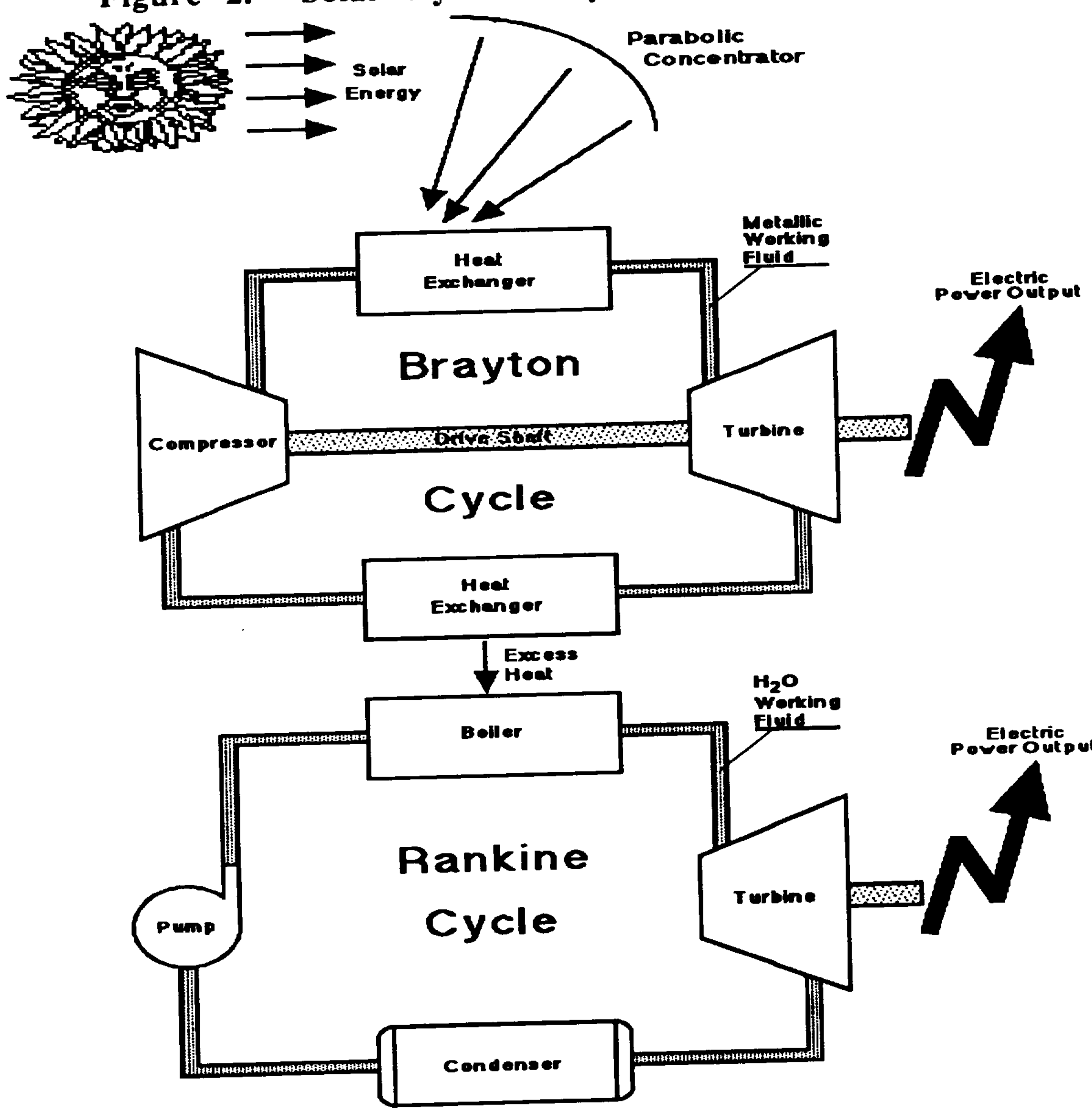


Figure 3. Block Diagram of Solar Dynamic System

However, the disadvantages of solar dynamic systems overshadow the advantages. Some of these disadvantages are that solar dynamic systems:

- use rotating machinery (turbines, pumps, etc.)
- require large thermal radiators
- lack flexibility and expandability
- are unproven in large-scale space applications
- may experience freezing of working fluids during SPS shadow times
- require frequent maintenance

Solar Photovoltaic Cells

Solar photovoltaic cells transform solar energy directly into electricity. The solar cell generates a current when light excites electrons from a semi-conductor's valence band to its higher-energy conduction band. Most spacecraft use panels of solar cells for some portion of their power generation. Large arrays of solar cells can be used to generate the large amount of power required for the SPS (see Figure 4). Using solar photovoltaic cells for energy conversion has several advantages. Solar photovoltaic cells:

- are a proven, low risk technology
- are light weight
- require little maintenance
- are low cost
- lend themselves to modular construction
- have seen recent technological advances increase their overall conversion efficiencies dramatically

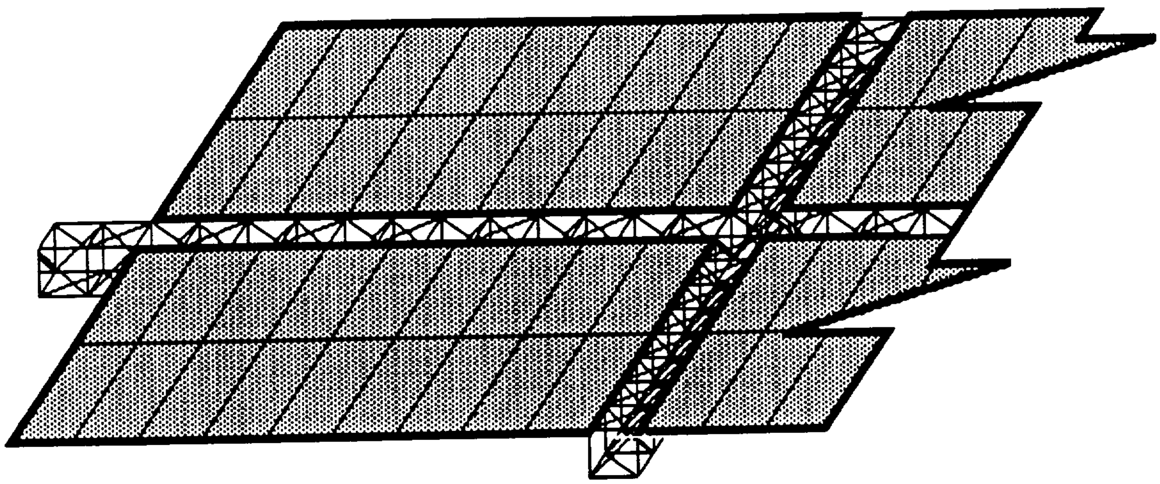


Figure 4. Solar Array Concept for SPS

Some of the disadvantages of solar photovoltaic cells are that they:

- require large collection areas
- experience performance degradation from radiation exposure

Selection of the Primary Energy Conversion Method

After completing research on these two types of energy conversion methods, solar photovoltaic cells were selected for use on the SPS. This selection was based upon a comparison of the relative advantages and disadvantages of the two conversion methods.

Selection of Solar Cell Type-Lens/Cell Approach

After selecting solar photovoltaic cells as the method of solar to electrical energy conversion, the Solar Technology subgroup focused attention on selecting the type of solar cell to be used on the satellite. Traditional solar cell technology uses single crystal silicon wafers as tiles to construct the flat plate solar panels used to power satellites.

Because these are virtually single crystal panels, they are expensive for large-scale electric power applications. Since the SPS is designed to generate 5 GW of power, it is not feasible to use this type of solar cell.

Attempts to reduce photovoltaic panel cost by abandoning the use of single crystal building has led to the development of amorphous silicon solar cells. These cells have been quite successful in low power applications such as light-powered calculators. Research indicates that this technology is not suitable for high power applications.

An alternative way of solving the problem of the cost of single crystal materials is to use plastic lenses to concentrate sunlight onto small-area single crystals. For example, a 10 cm^2 silicon cell gathers sunlight and produces 1.3 Watts at a cost of \$5.00. A 10 cm^2 plastic Frensel lens, costing \$0.50, could be used instead to gather the same amount of sunlight and focus it on a much smaller single crystal silicon cell to produce the same amount of power (1.3 Watts). The original 10 cm^2 wafer could be divided up into fifty smaller cells placed behind fifty lenses. The 10 cm^2 wafer would now be able to produce 50 x 1.3 Watts or 65 Watts. The cost of each concentrator solar cell unit might be approximately \$0.10 (or \$5.00 for 50 solar cell units) and the cost of a lens/cell concentrator unit (\$0.60) is considerably less than the 10 cm^2 single crystal silicon cell (\$5.00) [1:297-298].

This concentrator approach requires the lens/cell array to be pointed at the sun. This leads to a sun tracking requirement. The cost of the tracking is not offset by the additional power produced until array sizes of 4 square meters are reached. Since the envisioned SPS will involve square kilometers of panels, the drawback of the lens/cell approach does not apply to the SPS system [1:298].

The concentrator lens/solar cell approach has additional advantages over single crystal units. Since the cells are small and located behind lightweight optics, they can be shielded easily for improved radiation resistance leading to higher end-of-mission performance. Also, the use of smaller size solar cells leads to higher manufacturing yields. As Figure 5 shows, material utilization is 90% in the small concentrator cell approach, as opposed to 64% for the large flat plate solar cells.

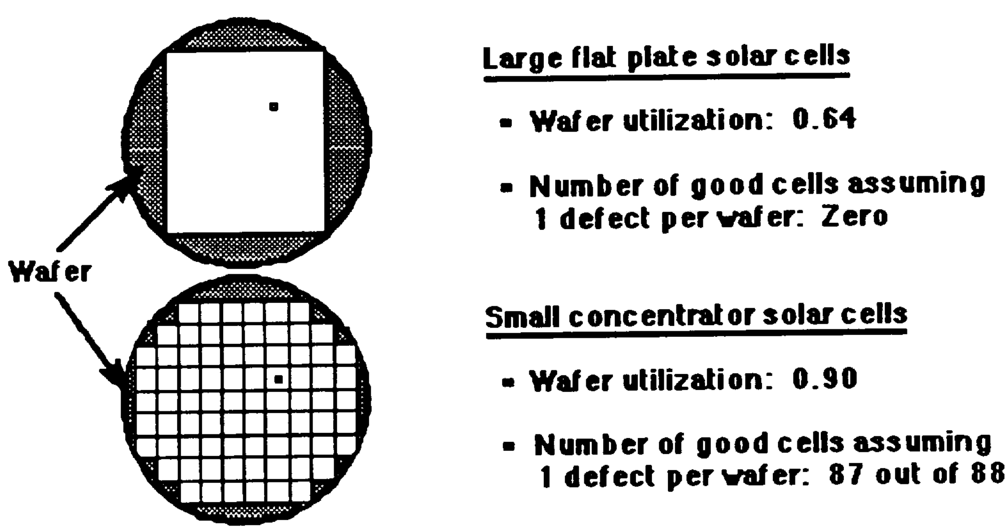


Figure 5. Small Concentrator Cells Lead to Higher Manufacturing Yields

High Efficiency Cells

In order to decrease the size and weight of the array panels used to generate 5 GW of power, the Solar Technology subgroup has focused their attention on selecting high efficiency solar cells. Figure 6 illustrates the impact of solar cell efficiency on array size.

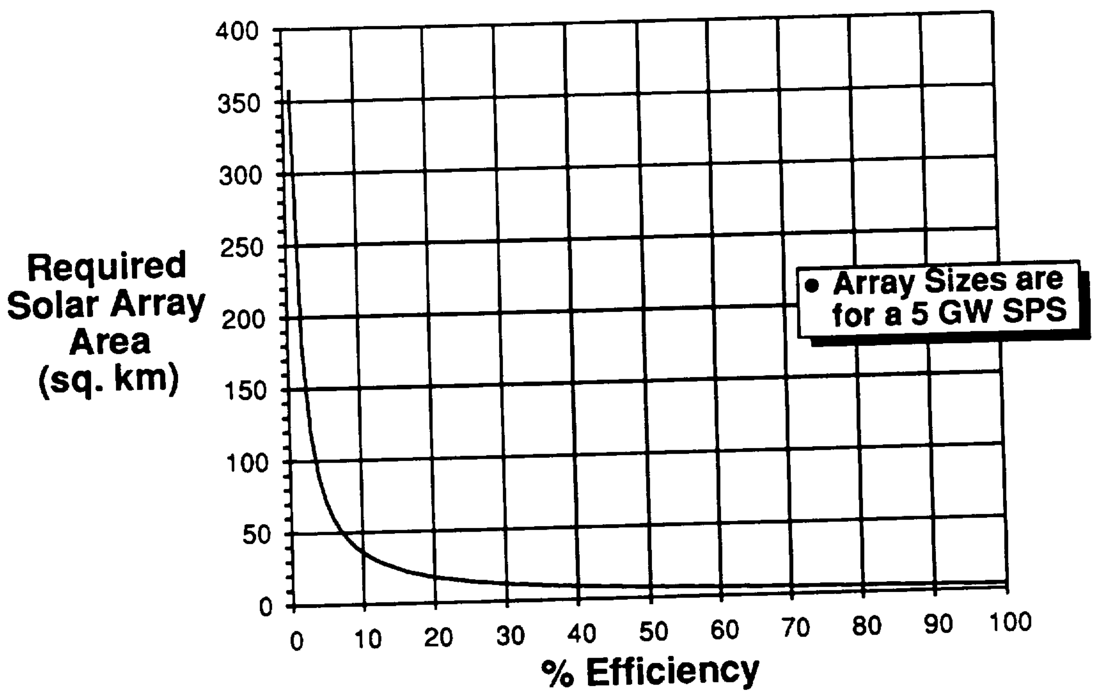


Figure 6. Impact of Cell Efficiency on Array Size

In the last decade, solar cells have consisted of a single layer of material converting a specific range of the solar spectrum to electricity. Efficiencies as high as 24% in the space environment, air mass zero (AM0), have been recorded using this approach. Recent breakthroughs in solar technology have led to the development of double and triple layer cells. These multi-layer solar cells can convert much more of the energy available in solar radiation by making use of semi-conductor layers that are sensitive to certain portions of the solar spectrum and transparent to others. Current work with two layer tandem cells has produced cells achieving efficiencies as high as 31% (AM0 at 100x concentration) [1:299]. Predictions have been made for three layer tandem cells with conversion efficiencies of 48.6% (AM0 at 100x). Such highly efficient cells are ideally suited for the SPS, resulting in a reduction of the number of cells and the size of array panels needed to produce 5 GW.

The Solar Technology subgroup conducted research to select the appropriate materials for each layer of the stacked cell. Research indicates GaAs is the prime candidate for the top layer. GaSb, is the material for the second layer. The most work remains to be completed in the manufacturing of the third layer. By the year 2000, based upon trends in solar technology, the major candidate for the bottom layer is InGaAsP [2:190-194].

Frensel Concentrating Lenses

To concentrate sunlight onto the solar cells and produce low cost electricity, inexpensive lenses are required. In addition, the weight of the lens is an important consideration for the SPS solar array. To reduce the cost of launching the array material into space, the weight of the lenses must be minimized. Lightweight, plastic Frensel lenses have been chosen for the SPS design. In addition to their low weight, the lenses can be manufactured easily and inexpensively in mass quantities [3:286-289].

Entech Prismatic Covers

In developing efficient multi-layer solar cells, each layer must be made transparent to certain wavelengths of light used in the lower cells. To accomplish this, the solid metal backing normally used to collect and conduct the current on conventional cells is eliminated. In its place is a grid of fine metal lines on the top of the cell that perform the same function [1:299].

To avoid losses in efficiency caused by the reflection of concentrated sunlight by the metal gridlines on the semi-conductor surface, cover lenses can be placed over each layer to bend incoming light away from the gridlines. Our research has indicated that the best source of these covers is Entech, a company in Dallas, Texas.

Solar Array Structure for Lens/Cell Assembly

The concept of a multiple stack concentrator cell is demonstrated in Figure 7. The concentrating lens is fixed above the stack (typically at a height of 1 inch). Light passes through the lens and is focused onto the smaller cell assembly where it first strikes an Entech prismatic cover. This cover bends the light around the metal gridlines on the surface of the solar cell, allowing the light to pass through [4:443]. Subsequently, the transmitted portion of the sunlight strikes the second and third solar cells of the multi-layer assembly. As shown in Figure 8, an assembled cell is mounted on a heat spreader which distributes any waste heat generated in the conversion of sunlight into electricity.

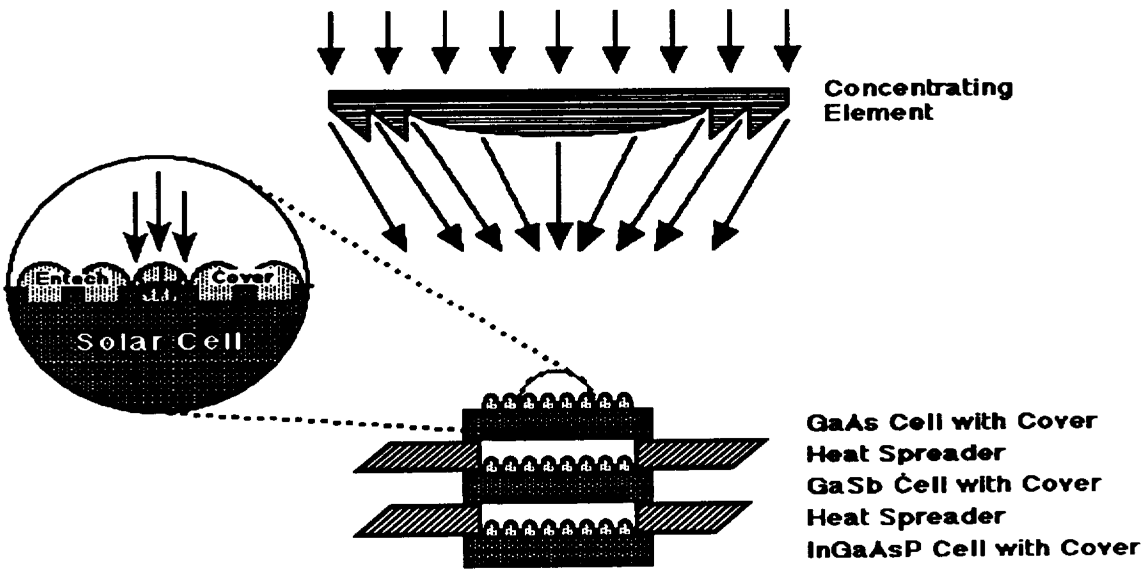


Figure 7. Multi-stack Solar Cell

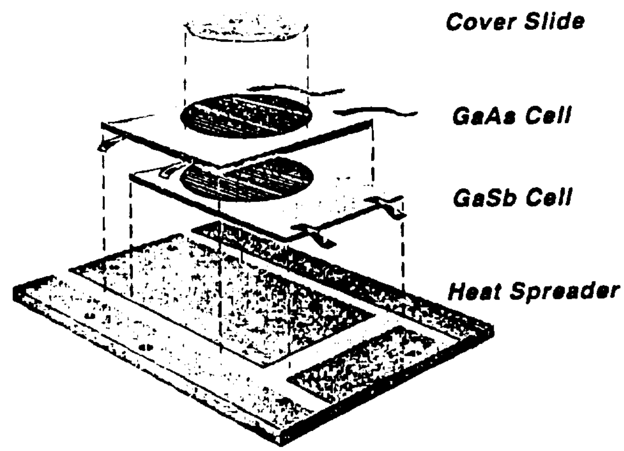


Figure 8. Cell Assembly mounted on Heat Spreader

To form a modular section of the SPS solar array panels, many of these lens/cell combinations will be placed in a honeycomb support structure as shown in Figure 9. The honeycomb support structure will also serve as a radiator for the solar cells, maintaining them at their operating temperature of 120 ^{o}C.

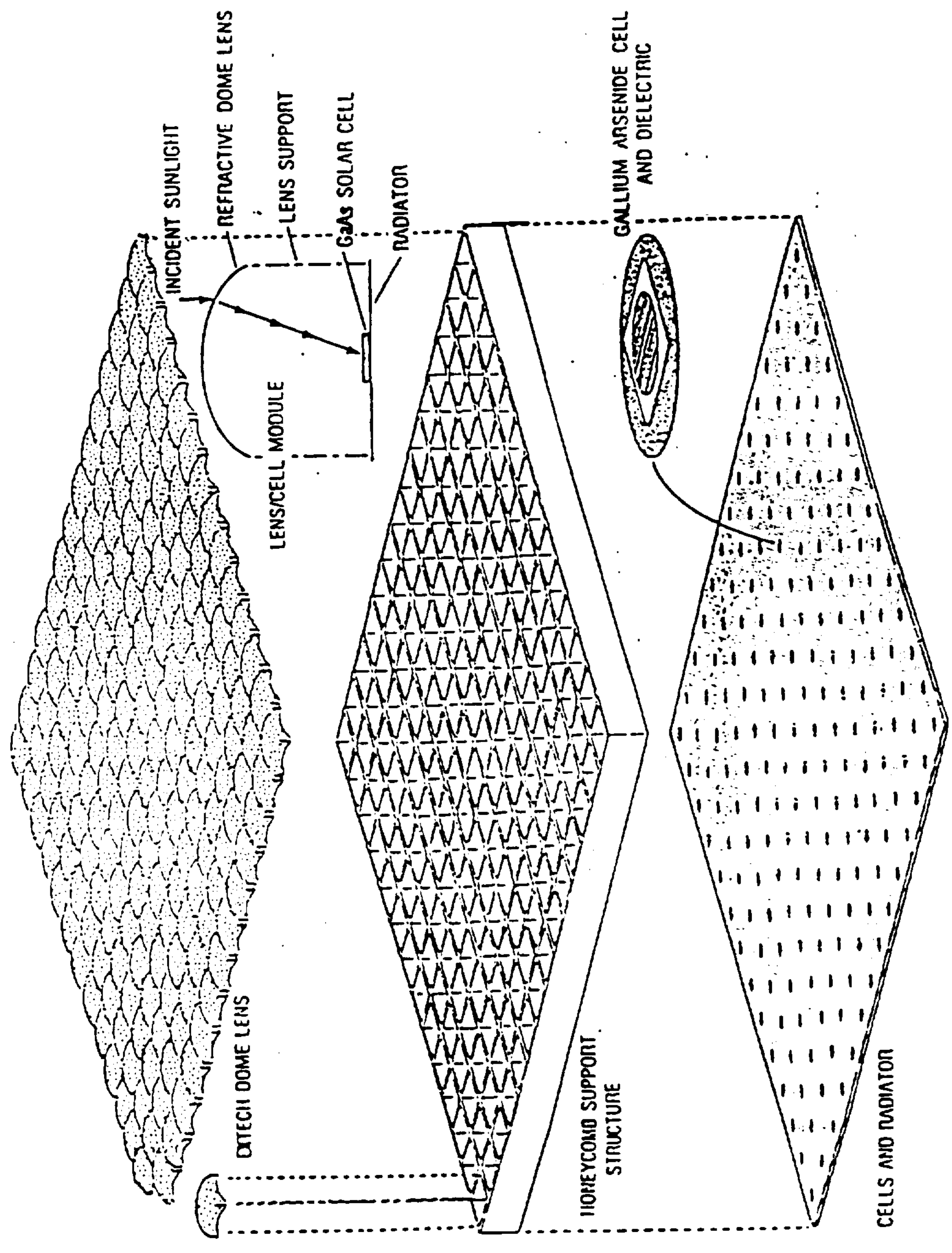
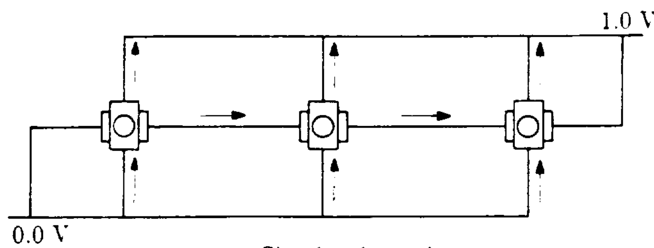


Figure 9. Honeycomb Support Structure

Depending on the voltages produced by each cell layer, the cells will be placed in an electrical circuit connected by flexible copper ribbons. The Boeing High Technology Center (BHTC) has developed a tandem lens/cell assembly consisting of an upper GaAs solar cell and a lower GaSb cell [1:297]. Since the lower layer generates approximately 1/3 the voltage of the upper GaAs cell, three GaSb cells are connected in series and three Galium Arsenic cells are connected in parallel as demonstrated in the schematic of Figure 10.



(a) Circuit schematic

(b) Flex circuit ribbon

Figure 10. Tandem Cell Circuit

Figure 11 shows the hardware used by Boeing's High Technology Center to create a triplet tandem cell circuit. Many of these triplets can be connected together to form larger array panels. This type of setup lends itself easily to the modular design desired for the SPS.

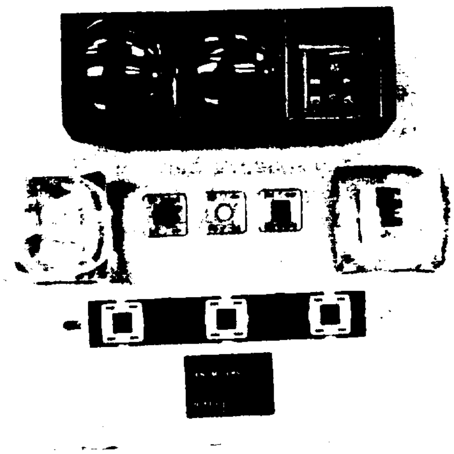


Figure 11. **Hardware Used by Boeing in Creating Tandem Cell**

2.3.2 Orbits and Controls

The solar sailing array panels (SSAPs) will be assembled at a space factory in low Earth orbit (LEO). All of the materials required for this will be sent up to LEO with a heavy lift launch vehicle (HLLV). This could be accomplished with a smaller vehicle, but even with a HLLV that can carry 2.5 $x10^5$ kg to LEO, this will take at least 165 launches.

Each SSAP will consist of a 1 square kilometer section of the solar array, four gimbled ion thrusters, two cylindrical pressure vessels that each contain 77200 kg of Argon, and an attitude reference determination system (ARDS). The configuration of the SSAP is shown in Figure 12. The ARDS consists of a CCD (charged coupled device) sun sensor, two CCD star

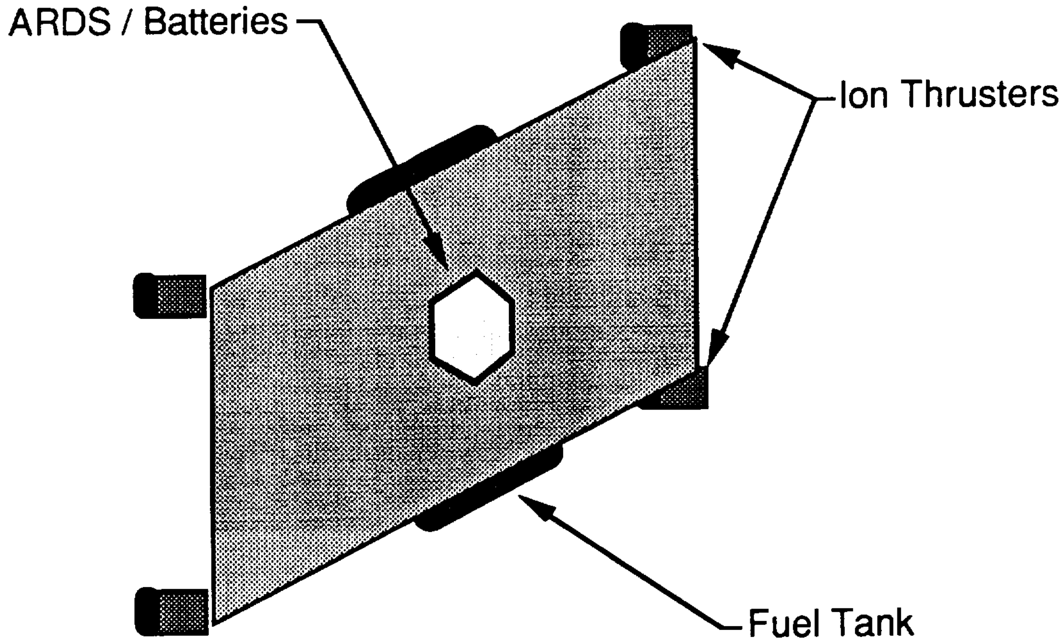


Figure 12. Configuration of a SSAP

sensors, a set of three rate gyros, and a processor that will interpret the sensor readings and control the thrusters. The total mass of each SSAP is 2.055 x 10^6 kg.

After the SSAP is assembled, it will spiral out with a constant low thrust to geostationary Earth orbit (GEO) where the fully assembled SPS will be. The SSAP will power itself with its solar array which will remain perpendicular to the Sun's rays. The SSAP will also have batteries for power during shadow. The batteries are discussed further in section 2.3.3. The total time of this transfer is approximately 150 days (*see Appendix E*).

Once the SSAPs arrive at GEO, they will be integrated into the SPS. This will be done by telerobotics. The thrusters and ARDS will be removed from each of the SSAPs and the SSAPs will be joined together to form the SPS. The thrusters will be attached to the corners of the SPS (20 at each corner), one pair of ARDSs will be located at each corner of the SPS, one pair will be located at the center of mass of the SPS, and one pair will be located on each side of the transmission dish. The processors will be removed from the remaining six ARDSs and evenly spaced along the SPS array and converted to monitor damage. The leftover sensor and gyros will be stored with the robots in case they are needed later as replacement parts. The final configuration of the SPS is shown in Figure 13.

The thruster system features an argon ion bombardment thruster reaction control system operating an average of 36 thrusters at a time. A total of 80 thrusters will be included to provide the required redundancy. This redundancy was based on the average annual maintenance interval and a 10000 hour thruster grid lifetime [7:201]. The thruster grids will be replaced annually by the robots. Each thruster will be gimbaled individually to improve the efficiency of the control system, to facilitate thruster servicing, to permit operation of adjacent thrusters during servicing, and to

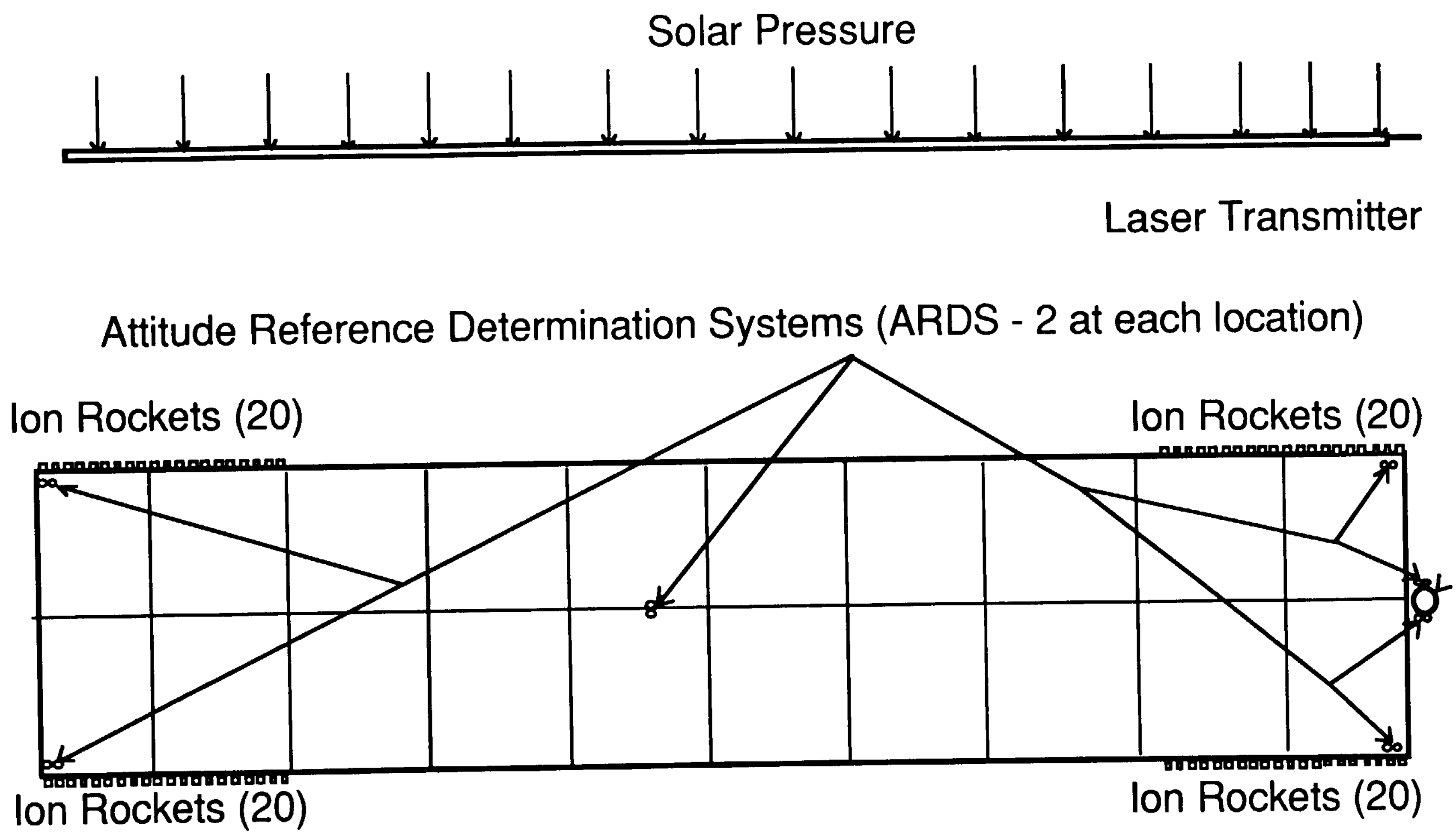


Figure 13. Location of ARDS and Thrusters

provide the redundancy. The thrusters nominally establish a force vector in the direction opposite the sun to counter the solar pressure force which is the dominant thruster requirement.

The thrusters are gimbaled through small angles and differentially throttled to provide the remaining forces and torques required for attitude control. The SPS will have to remain within 2 degrees of being perpendicular to the sun at all times [6:101-6].

Each thruster is an Argon ion bombardment thruster with a specific impulse of 13,000 seconds and a thrust of 23 Newtons. They require 1275 kW of power,and they have a restart time of 15 seconds and a one meter aperture. The thruster system will be controlled by the attitude control computer. The attitude control computer will receive its information for the processors in each of the ARDSs. The laser transmission computer will be in charge of pointing the transmitter, and the ARDSs on the laser transmitter will be used as a backup for the pilot beam. See the Computer section (2.3.6) of this report for more information on the computer systems.

A summary of the masses of the control system is shown in Table 1 and a summary of the masses of the SPS is shown in Table 2.

Table 1. Mass of Control System

Part	Mass, kg	Number on SPS	Total Mass, kg
ARDS	320	14	4480
Thruster	120	80	9600
Argon	154400/SSAP	20	3.088×10^6
Total			3.102×10^6

Table2. System Mass Properties

Subsystem	Mass, kg
Array	1.85×10^7
Transmission	5.67×10^7
Structure	1.39×10^7
Reaction/Control computers communications	3.10×10^7
15 % growth	6.17×10^7
Total:	4.73×10^7

2.3.3 Supplementary Power

The SPS's primary source of power will be the vast array of solar photovoltaic cells; however, there will be times when this power source is temporarily interrupted. As shown in Figure 14, the SPS will occasionally pass through the Earth's shadow and the solar cells will cease generation of electricity. The laser will stop transmission to the ground station. To maintain the survivability of the SPS, the critical systems will need an alternate source of power.

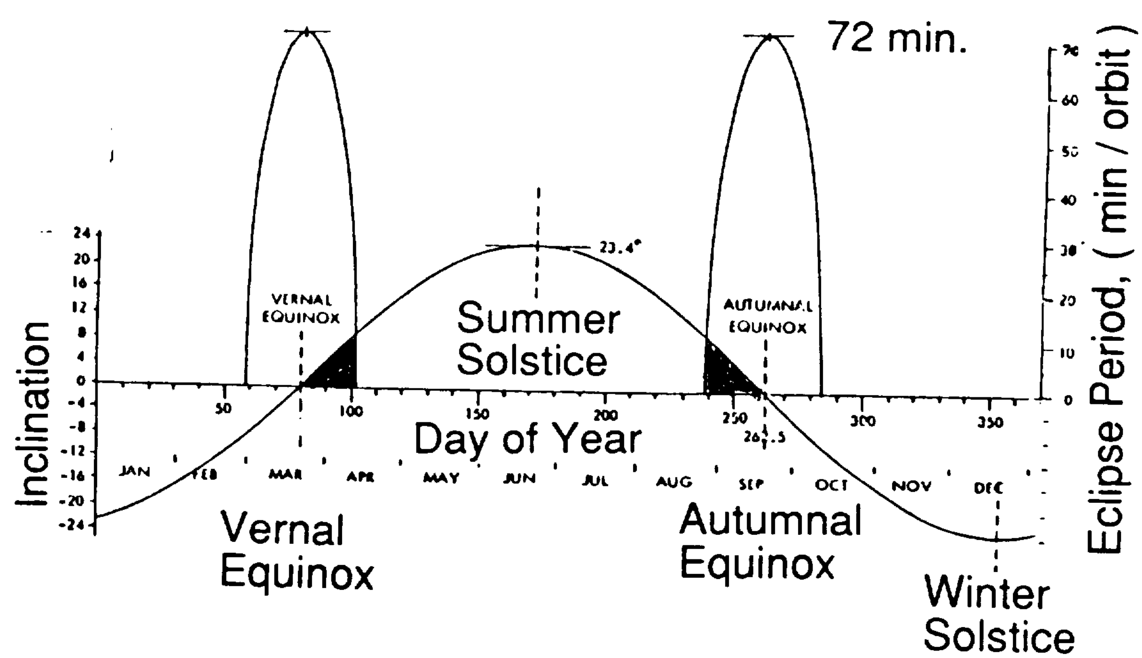


Figure 14. SPS Shadow Peroids at GEO

Sodium Sulfur batteries will provide the supplementary power. These batteries were selected based upon their relatively high power output, low weight, and high cycle life. The number of batteries required was calculated form the power density of the batteries and the maximum amount of shadow time (15 minutes per orbit) with a safety factor of 45 minutes in emergency cases. The total power provided by the batteries is 10 MWh at a mass of 50,000 kg (or .106% of the total SPS mass). The batteries will be transported from earth to LEO by a HLLV. When the SSAPs are transported from LEO to geosynchronous orbit, 500 kWh of batteries will be transferred with them.

The amount of battery powered needed is determined by the power requirements of critical SPS systems. These critical systems include: ACASK(four thrusters, sun and star sensors), Thermal Control (Heating/Cooling), computer systems, and communications. The reduced number of thrusters required compared to the nominal operating conditions of the SPS is due to the absence of solar radiation pressure when the sun is occulted. The thermal system remains operating in order to keep sensitive equipment at optimum operating temperatures. The computer and communications systems will maintain control by the ground station. Once the satellite is out of shadow, the solar cells will begin activating all SPS systems, including recharging the batteries for use in future shadow events.

2.3.4 Power Transmission

The purpose of the Power Transmission Subsystem is to receive power from the Solar Collection Subsystem and beam it to the ground station on Earth. The three areas of the Power Transmission Subsystem are labeled "A, B, and C" in the text that follows.

A. Choosing Between Laser and Microwave Transmission

The first and most important decision to be made regarding the Power Transmission Subsystem was to choose between laser and microwave as the mode of power transmission.

Laser and microwave were compared based on five different criteria: size of transmission optics, efficiency, flexibility of system, development of technology, and area of ground station required.

Size of transmission optics was considered the most important criteria. Due to its great wavelength, microwave transmission would require a transmitting antenna of about 1 km in diameter, weighing about 30,000,000 kg. Since lasers involve electromagnetic radiation, whose wavelength is around 10,000 times shorter than microwaves, the transmitting and receiving components can be 10,000 times smaller in diameter. We can scale the the laser transmission optics to be around 100 times smaller and the receiving area to be around 100 times smaller than those of microwave transmission. Depending on the type of laser chosen, the transmitting antenna will be 10m to 60m in diameter and weigh from 10,000 kg to 100,000 kg [8:F-1,F-2]. This reduced size allows for much easier transportation to space, and the small laser antenna may not need to be constructed in space, whereas space construction of the huge and delicate microwave optics could be a very complex and tedious process.

The next important criteria is electric to beam conversion efficiency. Laser conversion is estimated to have significantly lower efficiency (30% to 80%, depending on the type of laser) than microwave conversion (80% to 90%) [8:40]. This reduced efficiency would require our SPS to have greater area of solar arrays. In addition, the lower the efficiency of conversion is, the more energy we will have to remove to maintain the subsystem at its operating temperature, requiring a heat removal system greater in both size and complexity.

The third criteria for beam choice is flexibility of the beam to be used in a number of different orbits and for a number of different purposes. Because it requires a large receiving spot (about 1 km in diameter) microwave beaming could only be used in geosynchronous orbit to beam power to a ground station. Since lasers require small receiving areas (perhaps 10m to 20m in diameter), they could be used in a number of different ways. For instance, using laser beams, an SPS could be created with a number of relay satellites in LEO to provide constant power to the earth, or to provide power to a number of different ground stations. This could not be done using microwave beams because it would be highly impractical to design a relay satellite that could receive a beam with a diameter of 1 km, whereas a relay satellite could be easily designed to receive a beam 10m to 20m in diameter. Laser beams from our SPS could also be employed for aircraft propulsion or to provide power for spacecraft. These options may not be feasible using microwave beaming.

The final two criteria considered were development of technology and area of ground station. The microwave technology required for our SPS is quite advanced and well understood. The laser technology, however, is not nearly as developed and will require much research in the upcoming years. The area of the ground station is a relatively minor criteria, due to the fact that the cost of purchasing real estate may be considered negligible when compared to the other costs of this project. The amount of area required for a ground station to receive a laser beam (about 200 acres) is much smaller than the area required to receive a microwave beam (about 80,000 acres) [8:G-1].

The decision matrix in Table 3 shows that each of our five criteria was given a factor of importance, and laser and microwave were scored on each criteria on a scale of 0 to 10. In our decision process, laser scored almost twice as many points as microwave (111 vs. 58). As a result of this process, ASPEC chose laser as the best mode of power transmission for the SPS.

TABLE 3. MICROWAVE VS. LASER DECISION MATRIX

	CRITERIA	MICROWAVE		LASER	
(5)	SIZE OF DISH	0	0	10	50
(4)	EFFICIENCY	7	28	5	20
(3)	FLEXIBILITY	3	9	8	24
(2)	COMPLEXITY	9	18	5	10
(1)	SIZE OF GROUND STATION	3	3	7	7
	TOTAL	**58**		**111**	

B. Description of Laser Transmission Subsystem

The laser power transmission subsystem (LPTS) will consist of four major elements: electrical power supply, the closed cycle laser, heat removal, and optics. These elements are detailed in the following section. A side view of the LPTS is shown in Figure 15.

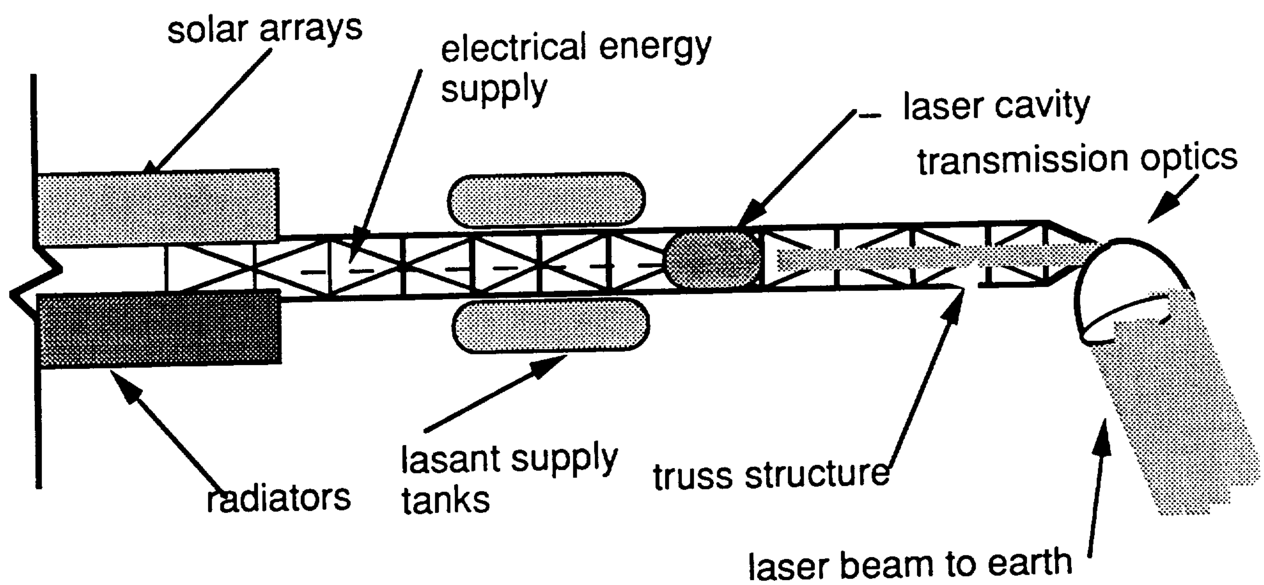


Figure 15. Laser Subsystem Side View (*not to scale*)

Electrical Power Supply

The LPTS will require some power conditioning of electricity that is produced by the solar arrays. This power conditioning is needed to convert low voltage, high current solar cell power into high voltage power for laser pumping. This can probably be done at an efficiency of 95% or higher [10:710].

Closed Cycle Laser

The next decision regarding the LPTS was to choose the type of laser to be used. The four types of lasers considered were the carbon dioxide laser, carbon monoxide laser, iodine solar pumped laser, and semi-conductor diode lasers. Other types of lasers were not considered due to low efficiencies, low reliability, or other factors that make them improbable candidates for our SPS.

Carbon Dioxide Laser

The first electrically driven laser developed was the carbon dioxide (CO_2) laser. It has a wavelength of 10.6 micrometers. For a geosynchronous satellite at about 40000 kilometer range, it will require a 60 meter diameter aperture to beam to a 10 meter diameter spot on the ground. As of 1989, the CO_2 laser is the most developed high power gas laser, has reached mega-Watt sizes, and promises an open cycle efficiency of greater than 60% operating at 409 Kelvin [10:711].

Carbon Monoxide Laser

The carbon monoxide (CO) Laser has a wavelength of 5 micrometers and requires a transmitter diameter roughly half the size of that of the CO_2 laser for a given range and reception area. The operation of the CO laser is very similar to the CO_2 laser previously mentioned except that the lasant gas must be kept at very low temperatures (about 60 K). Maintaining the lasant at this temperature requires a supersonic gas flow. The CO laser converts electric energy to radiation quite efficiently as small scale experimental CO lasers have reached 63% open cycle efficiency. However, the auxiliary power required for supersonic gas flow reduces the efficiency to about 30% for an overall system value. As of 1989, an efficient, continuous wave, mega-Watt sized CO laser still did not exist [9:77].

Iodine Solar Pumped Laser

Unlike the CO_2 and the CO lasers which are electrically driven lasers, solar pumped lasers are able to use solar power without conversion to electricity. These lasers may be uniquely suited to this project. Although solar pumped lasers are not as highly developed as the electrically driven lasers mentioned, they appear to stress materials and components less seriously than electrical lasers. Recent research of iodine solar pumped lasers estimates a direct solar to laser efficiency of only 0.6%. However, the wavelength of this laser is only 1.3 micrometers, requiring much smaller and lighter transmission optics than the two electrically driven lasers studied. The Iodine Solar Pumped Laser operates at a relatively high temperature of 486K; thus, less heat will need to be extracted to maintain the system at operating temperature, allowing for much smaller radiator areas [10:712,713]. With more research into advanced solar pumped lasers, this system may emerge as the preferred candidate.

Semi-conductor Diode Lasers

Electrically driven semi-conductor diode lasers may also be uniquely suited to our projected. Diodes made of semi-conductive materials have achieved 70% efficiency in the laboratory and 30% power efficiency and several Watts of continuous wave power per diode array in industrial use. Their emission wavelength is 0.85 micrometers. These diodes have excellent characteristics for space applications. They are high current, low voltage devices, and thus will required a minimum of power conducting circuitry when used with solar cells. Semiconducting devices, like these lasers, generally have long operating lifetimes. At an operating temperature of 300K, they will require a large and complex heat removal system. What makes semi-conductor diode lasers unique is that many low-power lasers can be coupled together to form one phase locked high power aperture [11:359,369]. This property is particularly useful to the SPS, because of the magnitude of power (5×10^9 Watts) required to be transmitted.

Choosing Type Of Laser

In choosing the type of laser beam, the iodine solar pumped laser and the semi-conductor diode laser were eliminated based on preliminary studies. The iodine solar pumped laser does not provide high enough efficiency to be used in the SPS, while the semi-conductor diode array would be too massive to implement into our system.

This preliminary elimination left two types of lasers as possible modes of power transmission: the CO laser and the CO_2 laser. The criteria used to choose between these two were: efficiency, operating temperature, development of technology, complexity of system, and wavelength. This decision was made utilizing the decision matrix shown in Table 4.

Efficiency was the most important criteria in choosing the type of laser. The CO_2 laser is estimated to have a slightly lower efficiency than the CO laser. As previously stated, a reduced efficiency in the mode of transmission would require our SPS to have a greater area of solar arrays, and also would require a heat removal system of greater size and complexity.

The operating temperature is another important criteria. The higher the operating temperature of the laser, the lower the amount of energy is that needs to be removed to maintain the lasant at the operating temperature. Operating at 409 K, the CO_2 laser has a significant advantage in this regard over the CO laser.

The CO_2 laser is the most highly developed high power laser beam, while CO laser research is somewhat less advanced. In addition, the CO laser would require a more complex heat removal system, due to the necessity of supersonic flow. Finally, the wavelengths of the two laser beams were considered because the wavelengths would directly impact the size of the optics. The CO laser has an advantage in this criteria.

The decision matrix in Table 4 shows that each of our five criteria was given a factor of importance, and the CO and CO_2 lasers were scored on each criteria on a scale of 0 to 10. In our decision process, the CO_2 laser scored significantly higher than the CO laser. As a result of this process, ASPEC chose the CO_2 laser as the type of laser to be used as the mode of transmission for the SPS. The mass to power ratio of the closed cycle laser is estimated to be 0.5kg/kw [8:42], which for our 5 GW system results in a mass of 2.5×10^6 kg.

Table 4. CO_2 Vs. CO Decision Matrix

Weight	CRITERIA	CO_2	CO
(5)	EFFICIENCY	7 / 35	8 / 40
(3)	OPERATING TEMPERATURE	8 / 24	2 / 6
(3)	DEVELOPMENT OF TECHNOLOGY	7 / 21	5 / 15
(2)	COMPLEXITY OF SYSTEM	7 / 14	3 / 6
(1)	WAVELENGTH	4 / 4	8 / 8
	TOTAL	98	75

Heat Removal

This element of the LPTS consists primarily of radiators. If we assume our CO_2 laser can operate at 80% efficiency, then 1.316 GW will be absorbed by the lasant and must be removed continuously to maintain the lasant at operating temperature. This task will be performed by radiators of nearly 1.22 square kilometers in area. This area can be further reduced by using heat pumps to aid in heat removal [12:635]. The radiators will be located near the transmission end of the SPS, underneath the solar arrays, as as shown in Figure 15, in order to protect the radiators from heating and solar degradation [13:31].

Optics

An adaptive optical system employing active controls to remove beam aberration aims and focuses the laser radiation. The transmitting aperture expands the narrow beam from the laser device and corrects for any beam distortion. In the design shown in Figure 16, a Cassegrain aperture configuration using a large concave primary mirror and a small convex secondary mirror is employed. On the secondary mirror, error sensors measure beam distortions and instruct the primary mirror to change its shape in order to provide for phase corrections. The primary mirror surface is composed of small mirror plates supported by five actuators on a reaction structure supported an a truss structure by coarse actuators. The combustion of these actuators and mirror segments conforms the primary mirror to the desired shape [9:78]. Using CO_2 laser the primary mirror will be 60 m in diameter, and the optics element of the LPTS will weigh about 100,000 kg.

The mass of the LPTS will be about 5.66 X 10^6 kg. The mass of each element of the LPTS is given in Table 5.

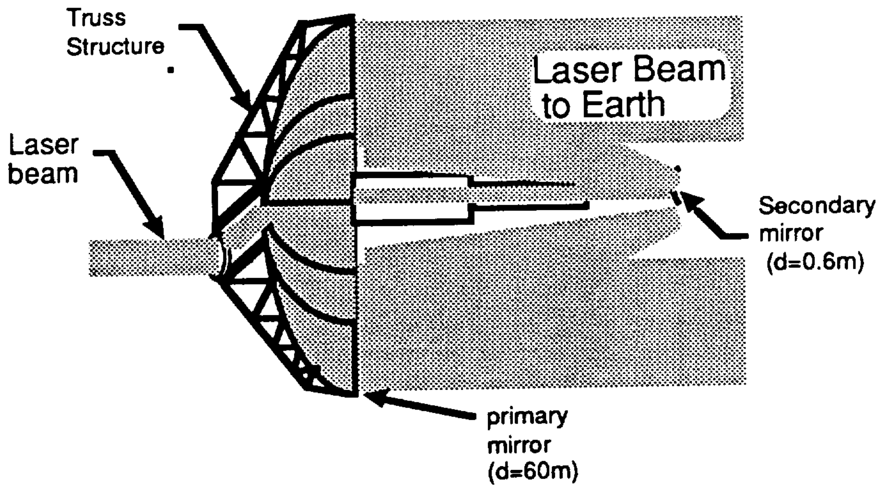


Figure 16. Transmission Optics

TABLE 5. Mass of LPTS Elements

ELEMENT	MASS (IN KG)
CLOSED CYCLE LASER	2.50×10^6
HEAT REMOVAL	3.06×10^6
OPTICS	0.10×10^6
POWER CONDITIONING	NEGLIGIBLE
TOTAL	**5.66×10^6**

C. Other Concerns

Safety

There are many safety concerns associated with beaming lasers to earth. The primary concern is the effect laser beams might have on humans in the vicinity of the reception site. This problem can be solved by fencing an area about the reception site (including a buffer zone), such that observation of the laser beam from outside the site will not result in eye or skin damage. Additionally, the ground station will be located in areas of sparse population, so as to further reduce the risk to humans.

Another safety concern is whether airplanes will be able to fly through this beam. A radiation level as high as 1.5 W/cm^2 is permitted for aircraft, but our system will beam as much as 10 W/cm^2 to the ground. Thus, we will have to restrict airplane flight in the vicinity of the beam [8:50].

ASPEC recommends that other safety concerns be investigated in further studies.

Environmental Concerns

The primary environmental effect of beaming lasers to earth is the effect the wasted heat (energy at the ground station not converted to electricity) may have on the climate. It has been found that only the local temperature and wind patterns (confined to the 200 acres of the ground station) will be affected by this wasted heat. The global climate will not be affected [8:49].

Another environmental concern will be the effect of this laser beam on birds and animals. The laser beam itself consists of a zone of concentrated power (about 10m to 20m in diameter) surrounded by a zone of low power (about 50m in diameter). Animals, obviously, would not be able to survive in the intense heat of the concentrated power zone. However, when approaching the laser beam, they should be able to sense the heat of the low power zone from a distance, and instinctively keep away [8:51]. Additionally, the location of the ground station will be chosen in an area where there is little animal life, so as to minimize this effect.

Rain clouds also present a problem. The inability of laser beams to penetrate rain clouds is an operational concern, as well as an environmental concern [8:48]. This problem can best be addressed by locating the ground station in an area that has a maximum number of clear days per year. The areas of the United States that have the most clear days per year are located in the Southwest (Arizona and New Mexico). There are areas in the Southwest that experience as much as 280 clear days per year [14:39].

Sociopolitical and International Concerns

A laser beam from outer space beaming large amounts of power may be a threatening proposition to people living near a ground station. This threat might be relieved by holding public forums to educate the public about SPS and ensure public safety. People living near a ground station might also be more inclined to accept the SPS if they learn of the economic benefits to their community that the SPS might have, like providing more jobs and increasing economic activity in the area.

There may also be international concerns of whether a laser system can be turned into a weapon and used for military purposes. Since any decision to use this system as a weapon will have to be deliberate and must be made during system design, these concerns can be somewhat remedied by making SPS subject to full disclosure and public, and even international, participation.

2.3.5 Structures

With a required solar array area on the order of 20 square kilometers (about seven square miles), the SPS will be by far the largest man made structure ever placed in orbit. Clearly, a structure of such enormous scale presents some formidable design challenges. The structure must be capable of efficiently handling any loads and torques experienced during normal operation, while retaining simplicity and relative ease of assembly. Weight must be minimized in order to reduce launch costs, yet the structure must be able to withstand the damaging effects of the harsh space environment.

Truss Design

The SPS supporting structure must be lightweight, easy to assemble and maintain while still efficiently handling all torques and vibrations applied to it. Forces of primary concern in the space environment include those due to atmospheric drag, solar radiation pressure, and impacting debris. The three truss designs, shown in Figure 17 are potential candidates for a supporting truss structure [12:232]. The tetrahedral truss shown in Figure 17(A) has the maximum load handling efficiency rating of three. This structure is exceptionally strong and stable since none of its members are in tension. The required solar arrays for this design are irregular, therefore, access is difficult and maintenance is more complicated. Figure 17(B) depicts and A-Frame design, which represents an attempt to design for ease of maintenance and repair. This particular structure includes members in tension, and as a result its load handling ability is limited, thus an efficiency rating of one. Finally, the Pentahedral truss, shown in Figure 17(C), combines ease of serviceability and load handling efficiency. This design contains no tension members while allowing access to the square sub arrays which easily lend themselves to modular design. As a result of these advantages, the pentahedral truss was chosen to be the primary supporting structure for the SPS.

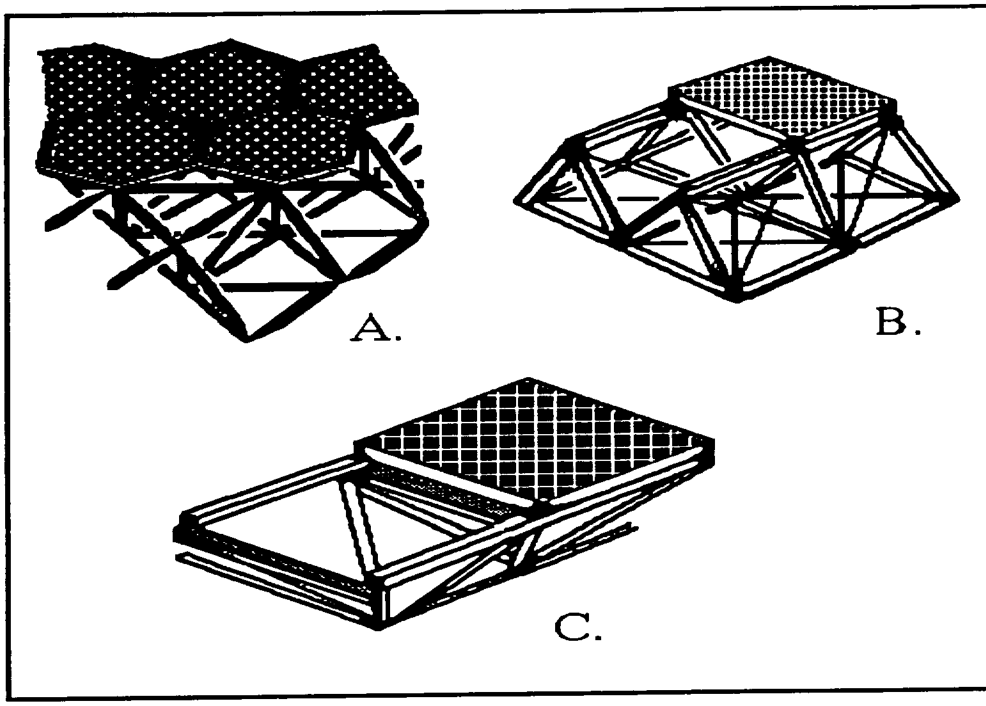


Figure 17. The Three Truss Designs Considered for the SPS

Structural Members

The individual truss elements will consist of tubular elements because they provide a strong, lightweight, and versatile alternative to conventional rods and beams. First, they possess the ability to handle shear stresses better than most other types of members, a very desirable property for a structure of this scale. Secondly, a tubular structure is inherently easy to assemble. Conventional joints may now be replaced by simple joints like those shown in Figure 18. Lug fittings, similar to those used to join pipes in conventional plumbing systems, will greatly ease assembly and directly lend themselves to a modular design.

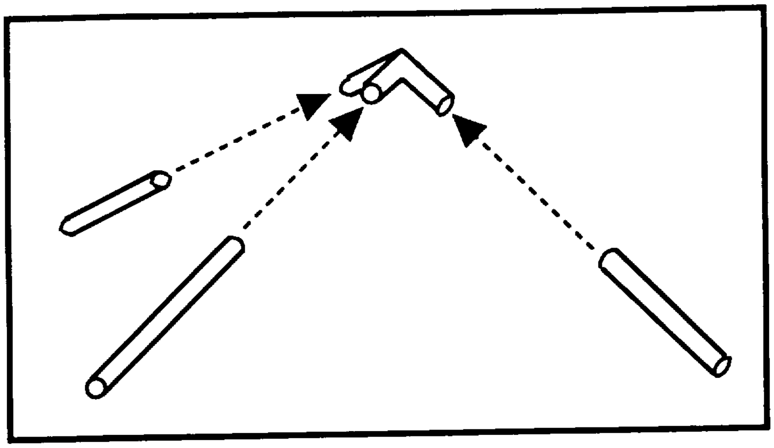


Figure 18. A Tubular Fitting

Finally, electrical wires may run directly through the tubes thereby allowing the miles of wiring necessary to carry electricity from the arrays to the transmitter to be insulated from the space environment. As a result of this installation, the likelihood of damage that would occur in external wiring will be greatly reduced.

Materials

The choice of materials is another important consideration in the design of the SPS structure. The materials used, like the truss, must be strong, lightweight, and able to withstand the harsh space environment over the course of the entire SPS design life, while suffering a minimal amount of degradation. Availability, low manufacturing costs, and a large amount of existing performance data make conventional alloys primary candidates for use as materials for structural members. Aluminium alloys feature a high stiffness to density ratio and excellent workability and a low level of magnetism. Unfortunately, aluminium's low yield strength may be prohibitive [13:209]. Newly developed high-tech aluminium alloys, however, are overcoming this problem [14:27-30]. Titanium has a substantially higher yield strength, while remaining non magnetic and possessing excellent corrosion resistance, but Titanium is difficult to machine and more costly to manufacture [13:210]. Both alloys would also require some kind of protective coating to protect them from the space environment.

Composites combine high strength, extremely light weight, low thermal conductivity, and tailorable elastic properties making them another worthy candidate for use as structural member materials. Effective oxidation coatings are essential, however, because even slight damage to the surface (which may be ignored with conventional alloys) can destroy the integrity of the composite fibers, resulting in a catastrophic failure. In addition to the special coating, electrical grounding must be achieved by using conductive strips located throughout the structure. As a result of these drawbacks, composites have been previously relegated to roles as secondary structures [13:211]. New developments in the field, however, are occurring at a rapid pace, and it is reasonable to expect that solutions to such problems may be found in the very near future [15:35-38].

As a result of these projected developments, composites have been chosen as the primary material for the SPS truss structure. Specifically the material data for Du Pont Kevlar 49 was used in all structural calculations. Kevlar 49 was selected primarily due to its exceptionally light weight, although its strength is somewhat lower than other high-strength composites. It is quite reasonable, however, to expect that high-strength composites as light or lighter than Kevlar 49 will be readily available by the year 2000. A comparison of high performance composites is shown in the table below.

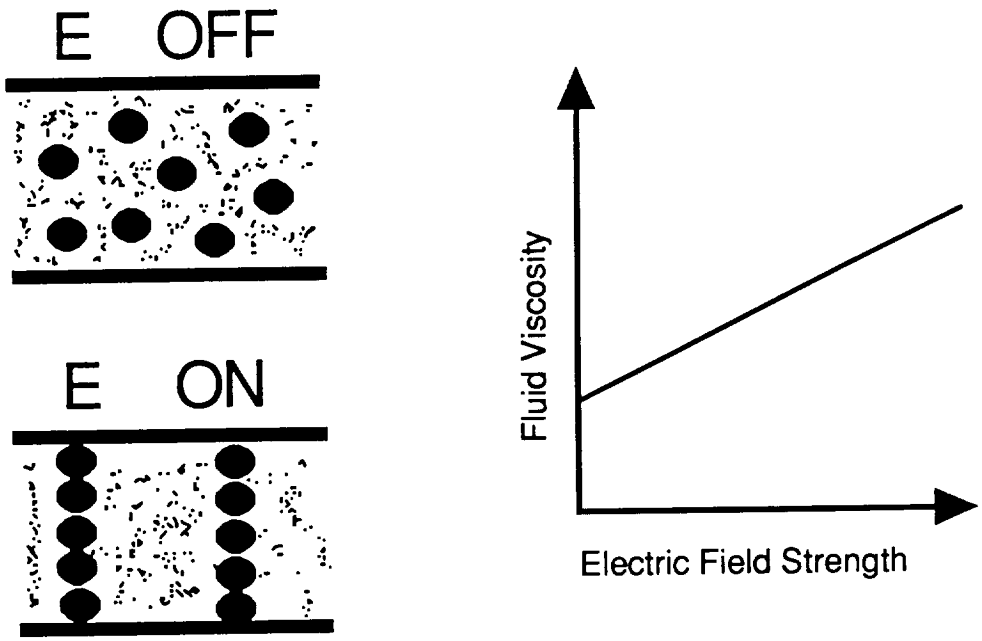
Table 6. Composite Fiber Comparison

Fiber Type	Specific Gravity	Young's Modulus	Tensile Strength
Boron	2.5	58 E 6 psi	450,000 psi
Carbon	2.2	60 E 6 psi	300,000 psi
Kevlar 49	1.45	19 E 6 psi	400,000 psi

Smart Structures

The large, flexible supporting structure required by the SPS will require an advanced structural control system. Active structural elements provide an innovative and practical solution to this problem [16:36-37]. These special members, which will be able to independently vary their damping coefficients, will be dispersed throughout the structure where they will automatically sense disturbances and act to minimize any damaging effects. These members are especially effective at suppressing vibrations, an area of great concern for a structure of this size.

Active members using electro-rheological (ER) fluids as a stiffening mechanism show particular promise [17:17-21]. As shown in Figure 19, ER fluids possess the unique property of a viscosity that varies with an applied electric field. Thus, as the electric field is increased, the viscosity continues to increase until the fluid eventually becomes solid. The effect is nearly instantaneous, and reverses as soon as the electric field is removed. As a result, a nearly immediate increase in damping to respond to structural perturbations is possible. Besides controlling the damping electronically, a structural increase in damping can be accomplished by using an elastomer between layers in the composite tubes. The inner and outer tubes can then shear independently and excess energy is absorbed in the elastic layer[18:79]. Figure 20 shows the composite tubing with the elastomer layer.



A. B.

Figure 19. ER Fluid Behavior
An electric field applied to an ER fluid causes the suspended particles to align into chains (A) which oppose the flow of the smaller fluid particles. These chains become stronger as the electric field is increased, resulting in a corresponding increase in viscosity (B).

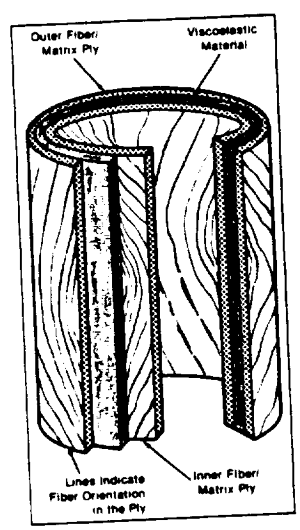


Figure 20. Multi-layered Composite Tube

Solar Array Structure

The solar arrays are somewhat brittle, and will thus require a supporting structure of their own. This structure will consist of a rigid but lightweight honeycomb backing which will allow the arrays to withstand the tensile and compressive loads resulting from vibrations of the SPS. The honeycomb structure will also allow easy mounting and removal of individual solar cell panels.

Sub-Structures

In addition to the array supporting structure and solar array backing, several smaller sub-structures will also be necessary. First, a separate structure to support the transmitter must be designed. It is critical that this structure be able to maintain its shape so that the transmitter can be pointed with the necessary degree of accuracy. The structure and its materials must therefore exhibit as little deformation as possible due to external forces and thermal changes. Next, housings for the lasers, control computers, and communications devices will also be required. These housings will be insulated in order to assist the subsystems in maintaining their respective operating temperatures. Finally, on-board energy storage devices will also require housings. These devices, if strategically placed throughout the array structure, could conceivably be used to help stiffen the overall structure. Such placement would further damp out any induced vibrations. It is important to note, however, that because of the huge scale of the array supporting structure, the effects of these sub-structures on the SPS as a whole will be minimal.

Modular Construction

Due to the sheer size of the SPS, it is not feasible to attempt to assemble the entire satellite in LEO and then transport it to GEO. Thus, the structure must be designed with some degree of modularity. In addition to making assembly easier, modular construction allows parts to be readily interchanged, which greatly improves the serviceability of the structure. Manufacturing is also greatly simplified, and may be performed at a lower cost since the same modules will be produced over and over again. Modular construction also makes the structure expandable so that additional solar arrays may be added in the future to increase power output.

The SPS will be constructed from a number of individual solar sailing array panels (SSAPs), as shown in Figure 21. Each SSAP is an independent module capable of generating its own power, and containing its own guidance and control systems. The SSAPs are in turn composed of smaller individual solar panels. These panels will also be incorporated into individual modules containing their own lenses, solar cells, and rigid backing structures. Thus, the solar panels are designed to be easily removed and replaced.

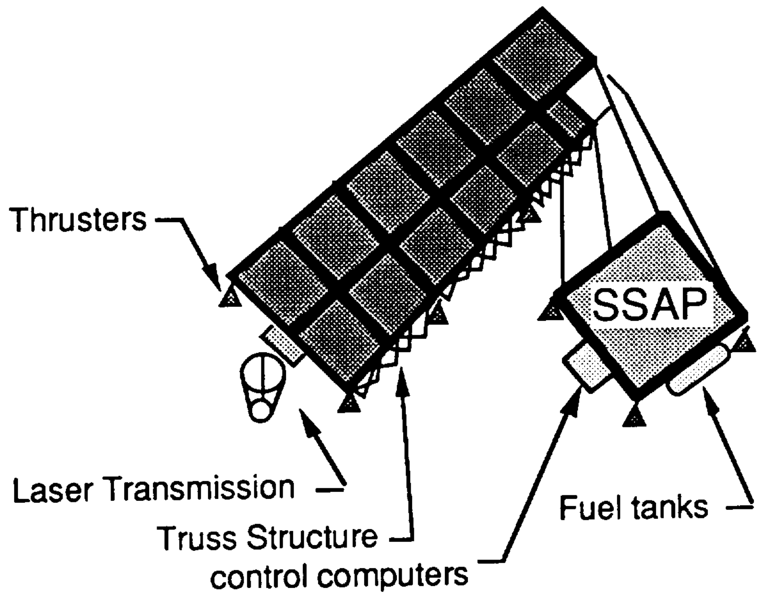


Figure 21. Robotic Construction and SSAP Integration Scheme

Construction of the SPS will take too long and be far too dangerous to make human assembly feasible. Thus, most of the assembly tasks will be performed robotically. Even though robots are much slower than humans, they have the ability to work around the clock without experiencing fatigue. As a result, the human role in the assembly of the SPS will be limited to that of inspecting and supervising the construction as well as performing any tasks the robots may be unable to complete. The use of telerobotics will be incorporated; humans will also control some robots when the construction cannot be automated. Use of robots will also simplify maintenance since several robots will be permanently stationed with the SPS in GEO. The robots will be constantly on duty, and thereby eliminate the need to regularly transport humans to the SPS to perform routine maintenance and repairs.

Launching the SPS

One of the major problems involved with the SPS will be launching all of its components into orbit. The most efficient way to accomplish this will be to manufacture the structural components in space. Thus the launches from Earth will primarily carry pre-processed materials into LEO where an orbiting "space factory" will extrude the tubular members and assemble the truss structures. This eliminates the need for a collapsible structure designed to fit inside the payload bay of a launch vehicle, which introduces unnecessary complexity and cost into the design. Prototype remote facilities for manufacturing structural members and constructing truss structures like the Grumman beam builder shown in Figure 22 have already been built and tested.

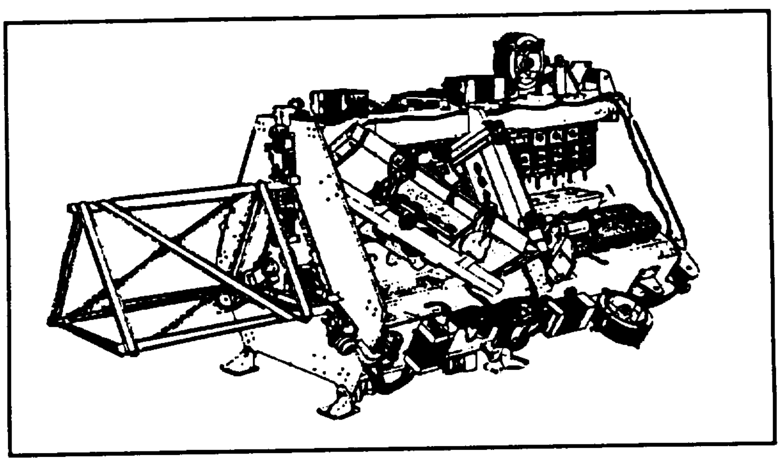


Figure 22. Grumman Beam Builder

Around 170 launches will still be required to get all of the materials into orbit. The number of launches, however, is still greatly reduced from that required to launch a prefabricated structure. The assembly scenario will involve assembling individual SSAPs in LEO and individually transporting them to GEO, where the final assembly will be performed entirely by robots. The primary steps in assembly of the SPS are as follows:

1. Establish a "space factory" in LEO with facilities to manufacture the structural elements and assemble the SSAPs.

2. The pre-processed structural materials will be launched for manufacture of structural elements. The solar panels will be manufactured on Earth and launched for assembly in LEO.

3. The truss structure will be assembled from its individual elements and solar panels will be mounted until an entire SSAP is produced.

4. The SSAP will be transported to GEO using ion thrusters powered electricity generated by the SSAP itself.

5. Final assembly will occur in GEO as robots assemble the arriving SSAPs to form the operational SPS.

Robotic Maintenance

Robots will be used extensively to perform both routine maintenance and unscheduled repairs to the SPS. The robotic maintenance system will be primarily composed of two robots mounted on railing fixed to the SPS. As shown in Figure 23, the mounting rail will move the robots over the length of the SPS, while the robots themselves will move transversely along the rail. This system, which operates much like an ordinary computer plotter, allows any point on the SPS to be easily reached.

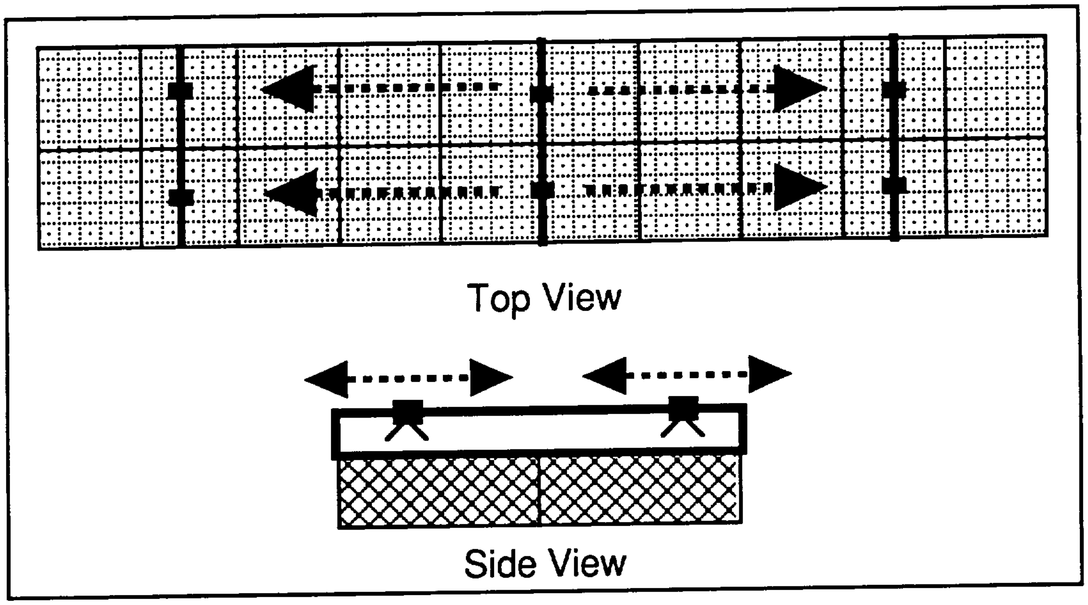


Figure 23. Rail Mounted Robot Concept.

These rail mounted robots will be primarily used to perform routine repairs, especially replacement of damaged solar cells. The mounting rails will extend around the edge of the SPS to allow the robots to service the rear of the structure. They will also be stowed at the rear of the SPS when not in use.

In addition to the rail mounted robots, a single free floating robot will also be used. This fully maneuverable robot will be used to perform repairs in remote areas that may be inaccessible to the other robots. Other duties will include remote inspection, maintenance and repair of the rail mounted robots, and debris control.

A supply of spare parts for frequently replaced items (i.e. solar cells) will be incorporated into each SSAP during initial assembly in LEO. Once these supplies begin to dwindle, additional parts will be shuttled up to the SPS as needed. Direct human involvement will only be required if a problem arises that is too complex to be handled entirely by the robots. Thus, human involvement is not considered a part of the regular maintenance schedule.

Design Considerations

Other problems that must be taken into account in the design of a structure of this size include space debris and thermal effects.

Space Debris

Since the SPS is a structure of enormous area (20 square kilometers), minimizing the damage due to impact from space debris and meteorites is of utmost concern. In fact, the question here is not whether the SPS will be hit by any space debris, but how often, and how severely. First, some sort of transparent covering will be essential to protect the fragile solar arrays from these hits. The transmitter must also be designed to resist such damage. As a result, both the solar array and the transmission structures will be designed to allow easy replacement when necessary. Back-up transmitters, computers, and other redundant systems will also be in place so that normal operation can continue if the primary systems should fail. An active damage monitoring system will also be incorporated so that damage to any part of the SPS can be quickly pinpointed and repaired without any significant interruption in the system's operation. A debris detection system will also be incorporated so that areas likely to sustain impact damage can be anticipated. This system will allow maintenance robots to be standing by, ready to repair damage as soon as it occurs.

Thermal Effects

Thermal effects on the SPS structure are another primary design consideration. Adverse effects of thermal gradients on the structure, such as thermal expansion and contraction of structural members, must be minimized. Furthermore, thermal cycling during the brief periods when the SPS passes through the Earth's shadow (about 90 cycles per year), and the resulting thermal fatigue, must be accounted for. Since the SPS is designed to maintain a constant orientation with respect to the sun, design of the SPS components should be optimized to take advantage of the relatively constant thermal gradient.that results.

2.3.6 Computers

The on-board computer system for the SPS will be comprised of a network of five computers (Figure 24). A master control computer, tied to ground control via a communications link, will oversee the operations of a thermal supervisory computer, power distribution computer, attitude control computer, and a laser transmission computer [19:4-35].

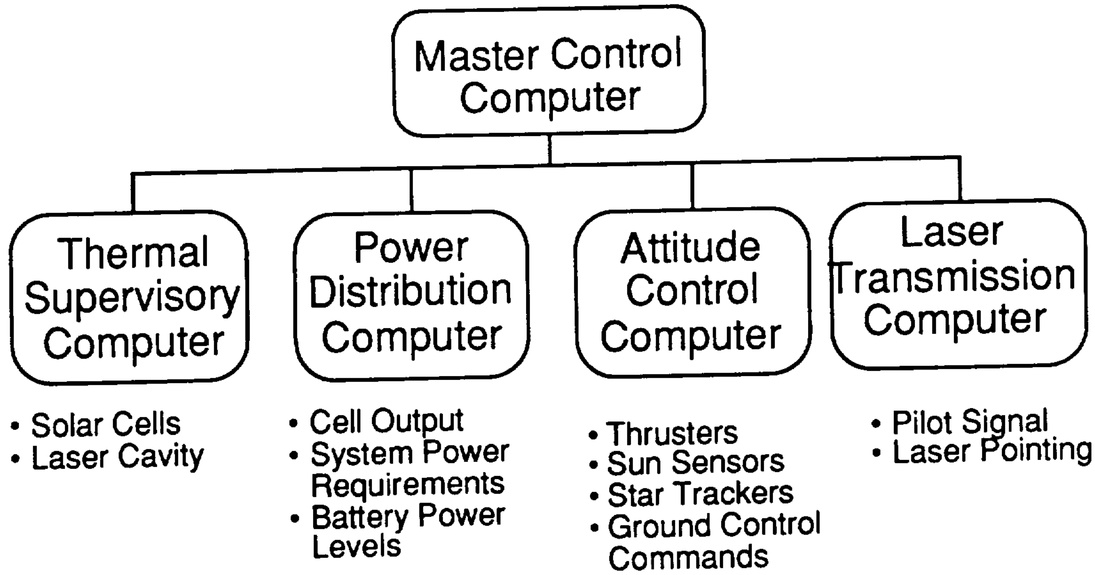


Figure 24. Computer Subsystem Elements

Master Control Computer

Occasionally, ground control will need to override the SPS on-board computer systems for orbit corrections, repair missions, etc. The master control computer will provide ground control with this capability as well as a means of shutting-down the SPS during emergency situations.

Thermal Supervisory Computer

Subsystem components, such as the laser cavities used in power transmission, require that certain operating temperatures be maintained for efficient, damage-free operation. The thermal supervisory computer will be responsible for monitoring the thermal conditions of SPS subsystems and will take corrective action to maintain subsystem operating temperatures.

Power Distribution Computer

Over the lifetime of the SPS, power output from the solar arrays will decrease due to damage from solar/cosmic radiation and space debris impact. The power distribution computer will monitor power output to provide ground control with the location of highly damaged array modules. Furthermore, because SPS power requirements will be different when the satellite is in shadow, the power distribution computer will also serve as a power manager, shutting down unnecessary systems during SPS shadow times and restarting them after the satellite passes out of shadow.

Attitude Control Computer

Orbital perturbations and the need to maintain a constant attitude with respect to the sun translate into a need for an attitude control computer. The attitude control computer will manage a network of individual SSAP processors to control the SPS. Already mounted on each SSAP for orbit and attitude control during its 150 day LEO to GEO transfer, the SSAP processors will work in conjunction with the attitude control computer, supplying it with information on SPS orbit and attitude, and activating desired thrusters. Since not all of the SSAP processors will be needed, the excess processors will add redundancy to the system. Ground control computers will also be able to send commands via the master control computer to the attitude control computer.

Laser Transmission Computer

Precise pointing of the SPS laser beam is one of ASPEC's primary concerns. The laser transmission computer, locking onto a pilot signal from the receiving station, will keep the laser beam accurately pointing toward the receiving dish. In the event that the pilot signal is lost, the laser transmission computer will automatically shut-down laser power transmission.

2.3.7 Communication

Communications link the ground, robots, and subsystems of the SPS together. Currently, a high frequency pointing link will be used to assure the accurate pointing of the laser beam. Ground commands will be carried via TDRSS during SSAP assembly and transfer. A ground station will assume this role once a SSAP reaches its GEO destination. Robotic assembly scenarios considered require that the robots be primarily autonomous, with telerobotic capabilities for specific jobs that require this feature.

2.4 System Problem Scenarios

Several possible worst case scenarios and possible solutions are outlined below.

Worst Case Scenario	Solution
SPS becomes controlled by destructive organization/person	Critical self destruct activation
Fail-safe mode for transmission pointing fails	Critical self destruct activation
SPS suffers massive damage from a meteor shower	Robots remove least damaged panels and move to start-up configuration locations
Loss of attitude/reaction control and SPS begins to tumble	Release tethered thruster modules to despin SPS
Catastrophic failure of a major subsystem	Send up more parts from LEO

Note: Critical self destruct does not actually destroy SPS, it merely becomes inoperable.

2.5 Project Deliverables

Upon the completion of this contract, ASPEC will provide a comprehensive design for a Solar Power Satellite that will convert energy from the sun into electricity and beam it down to Earth cleanly and safely. The SPS will be designed to provide 5 GW of electric power continuously during its 30 year service life. The design will take advantage of expected innovations in solar collection technology, electric power transmission, advanced materials, structural design, and construction techniques in order to make the SPS as efficient and economical as possible. A model of the SPS and a

2 ft x 3 ft poster highlighting the primary aspects of the design will also be provided.

3.0 Management

3.1 Management Structure:

The management organization is divided into the positions of Project Manager, Chief Engineer, Department Managers, and Engineers (Figure 25). The Department Managers are responsible for coordinating the studies in an individual area of work. The Chief Engineer coordinates the technical activities of each department. The Project Manager will act as a liaison between ASPEC and the contract monitor and serve as the executive officer for the Configuration Management team which is composed of the Project Manager and the Chief Engineer.

3.2 Program Schedule:

Management of ASPEC's SPS project is designed to be flexible and effective. The tasks in RFP # SPS-A1-91 will be accomplished by a management structure that provides interaction between all areas of work. Additionally, task force groups are formed to ensure that each milestone defined in our program schedule is accomplished and will also guide the team in other specific tasks such as the University of Houston and NASA/USRA presentations.

Areas of work are defined in each of the separate phases of the program. While some areas will exist through several phases; others will be completed and personnel assigned to other tasks. Engineering personnel are expected to adapt to meet the changing needs of the tasks in the program schedule. The critical path schedule (Figure 26) was developed to help guide project members in accomplishing their tasks. Personnel finishing their studies in one area will then begin the next task required for project progress. Priority will be given to areas that are critical paths in the current phase. The timeline chart (Fig 27) shows the phases and milestones in the program.

Task teams will be formed for each phase of the program and will act as a coordinating body that oversees the achievement of the goals for that phase. Personnel in the task teams will be rotated at the end of each phase to avoid interference with conflicting commitments in other study areas. Group meetings are held three times a week in order to allow problems to be rapidly identified and corrected.

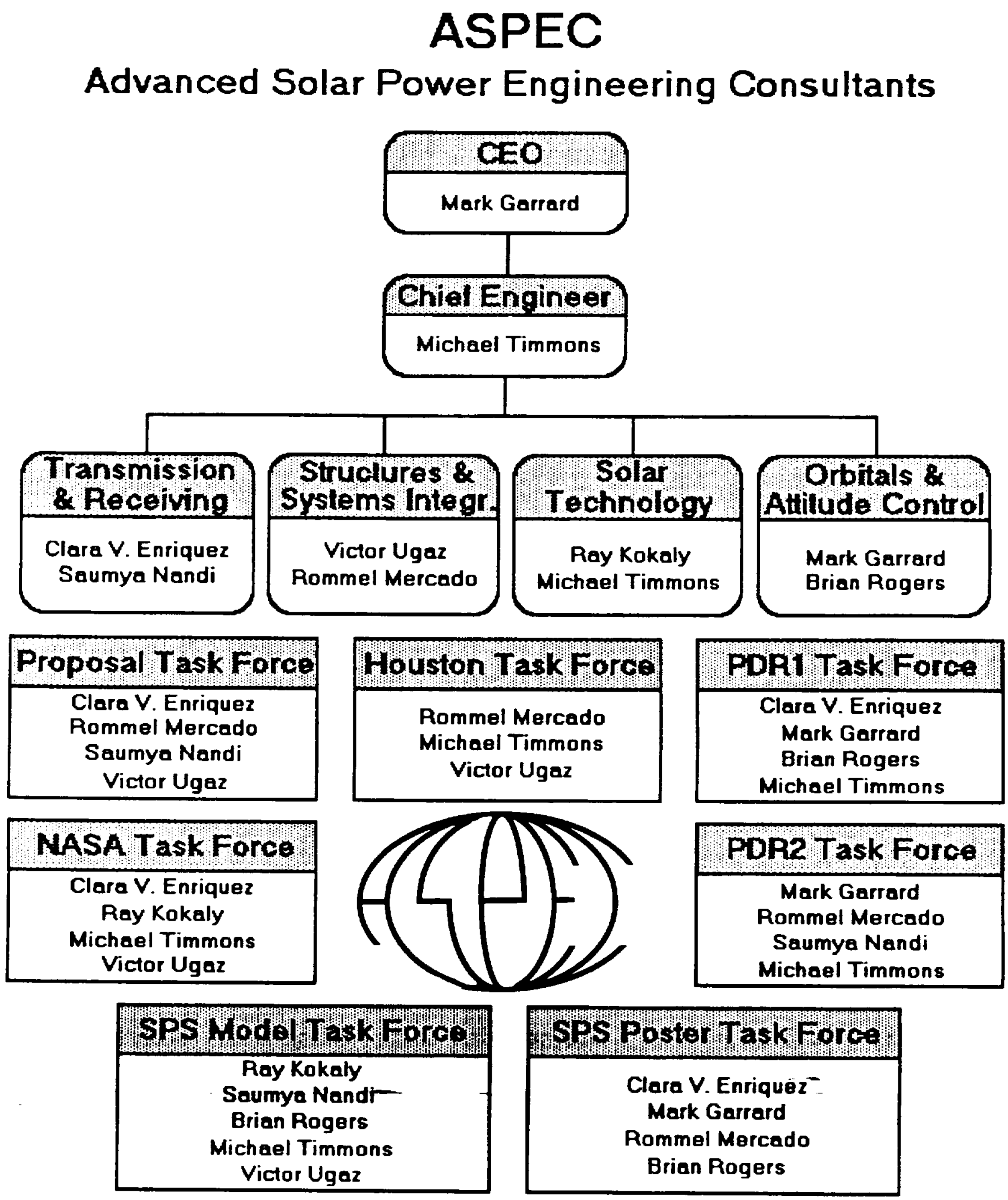
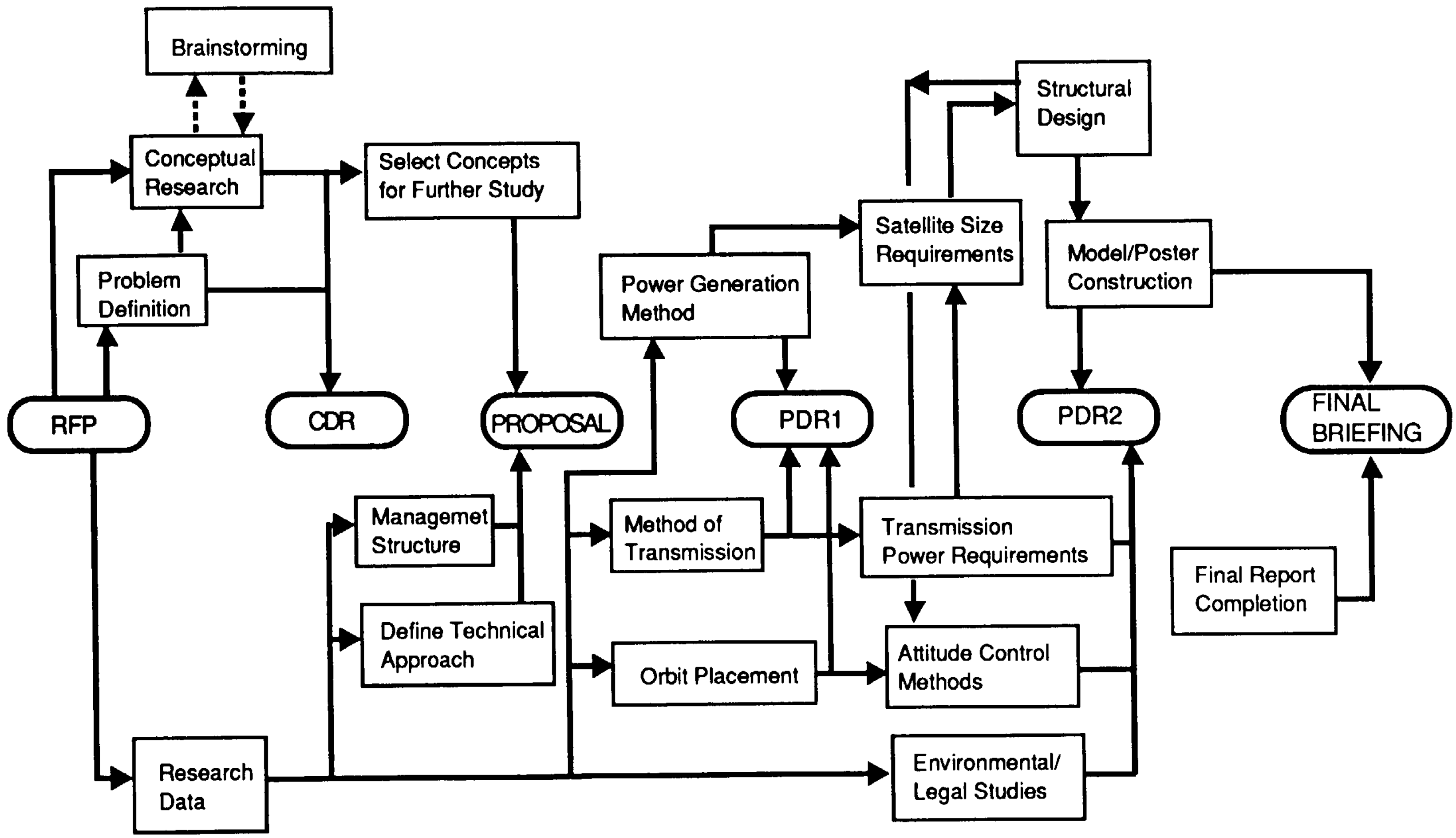
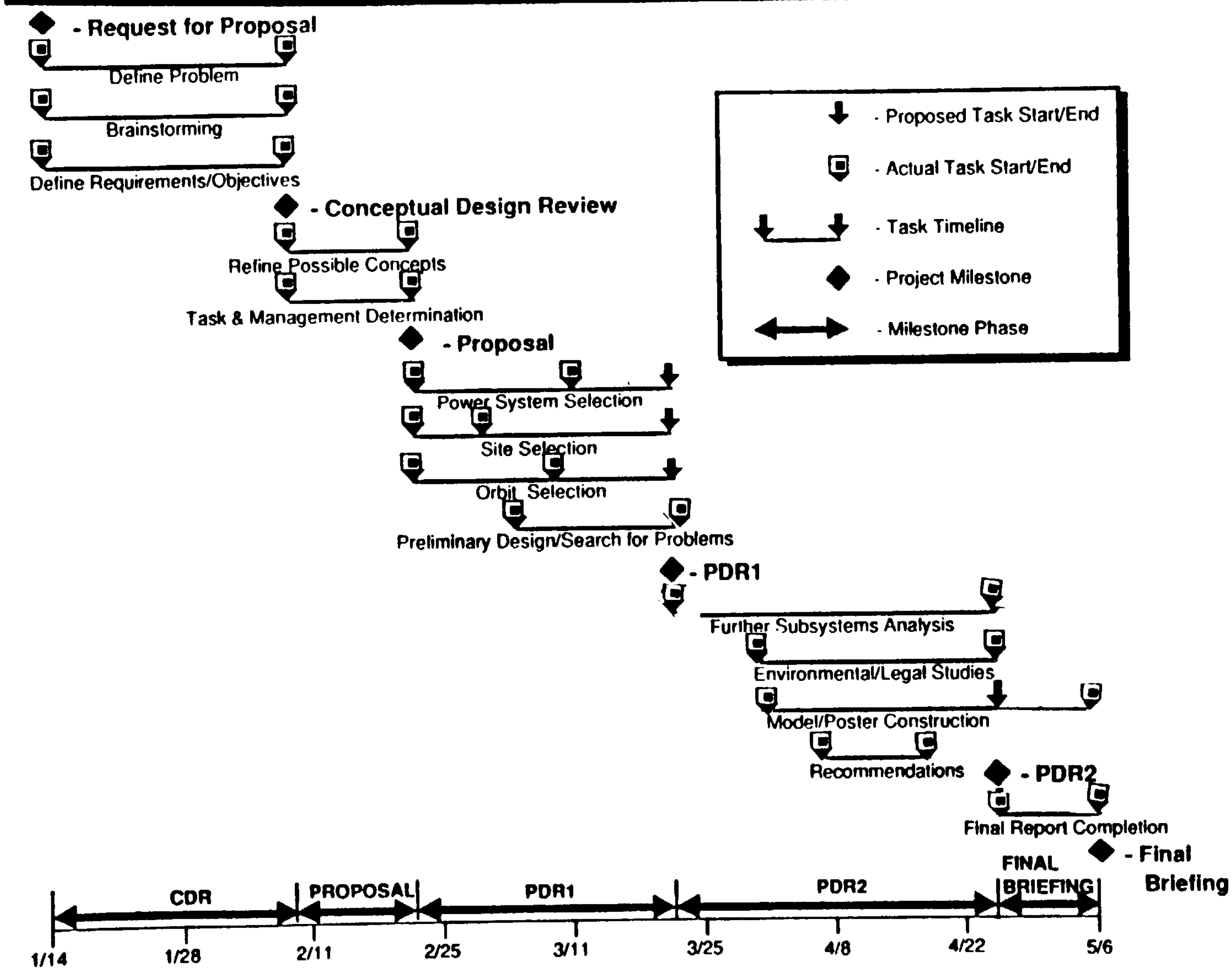


Figure 25. Management Organization



Critical Path Flow Chart

Timeline & Milestone Chart



3.3 Project Costs

ASPEC's costs for conducting this SPS study have generally remained close to the costs estimated in the proposal as illustrated by Figure 28. From this cost comparison chart, it can be seen that during week 9, ASPEC went over budget for the first time since undertaking this project. This is attributed to the unexpected increases in personnel workload caused by the University Space Research Association (USRA) presentation at The University of Houston during that week. Figure 29 illustrates how the personnel workload for week 9 was more than double the estimated amount. Upon completion of this project, ASPEC finds itself only $140.00 over budget as compared to almost $2000.00 over budget during week 10.

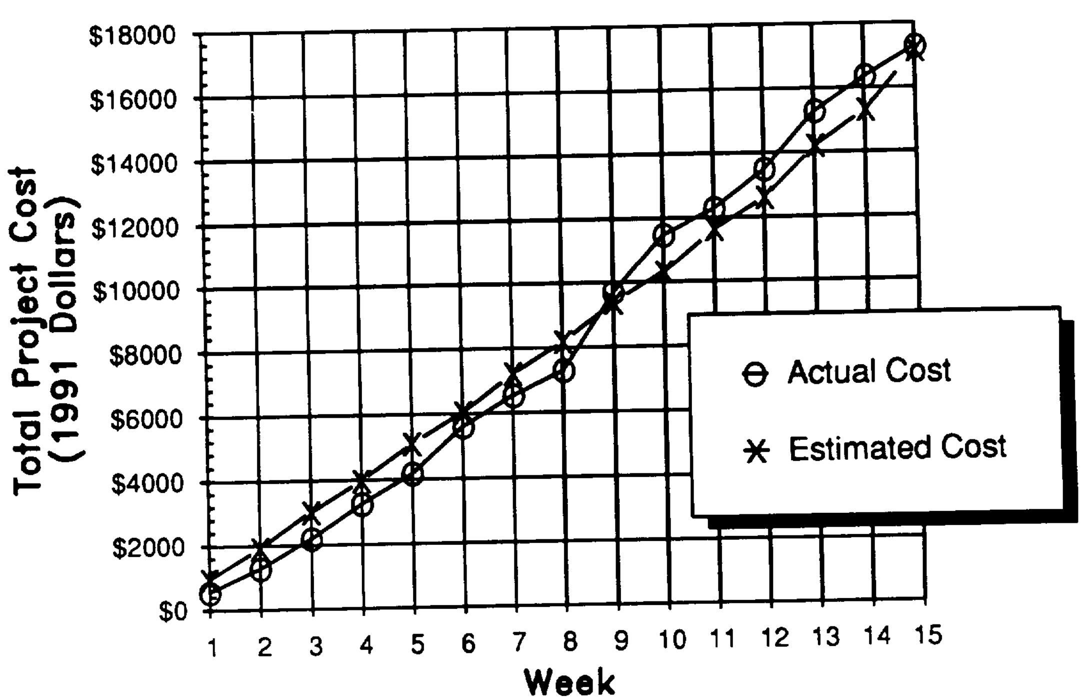


Figure 28. Comparison between Actual and Estimated Cost

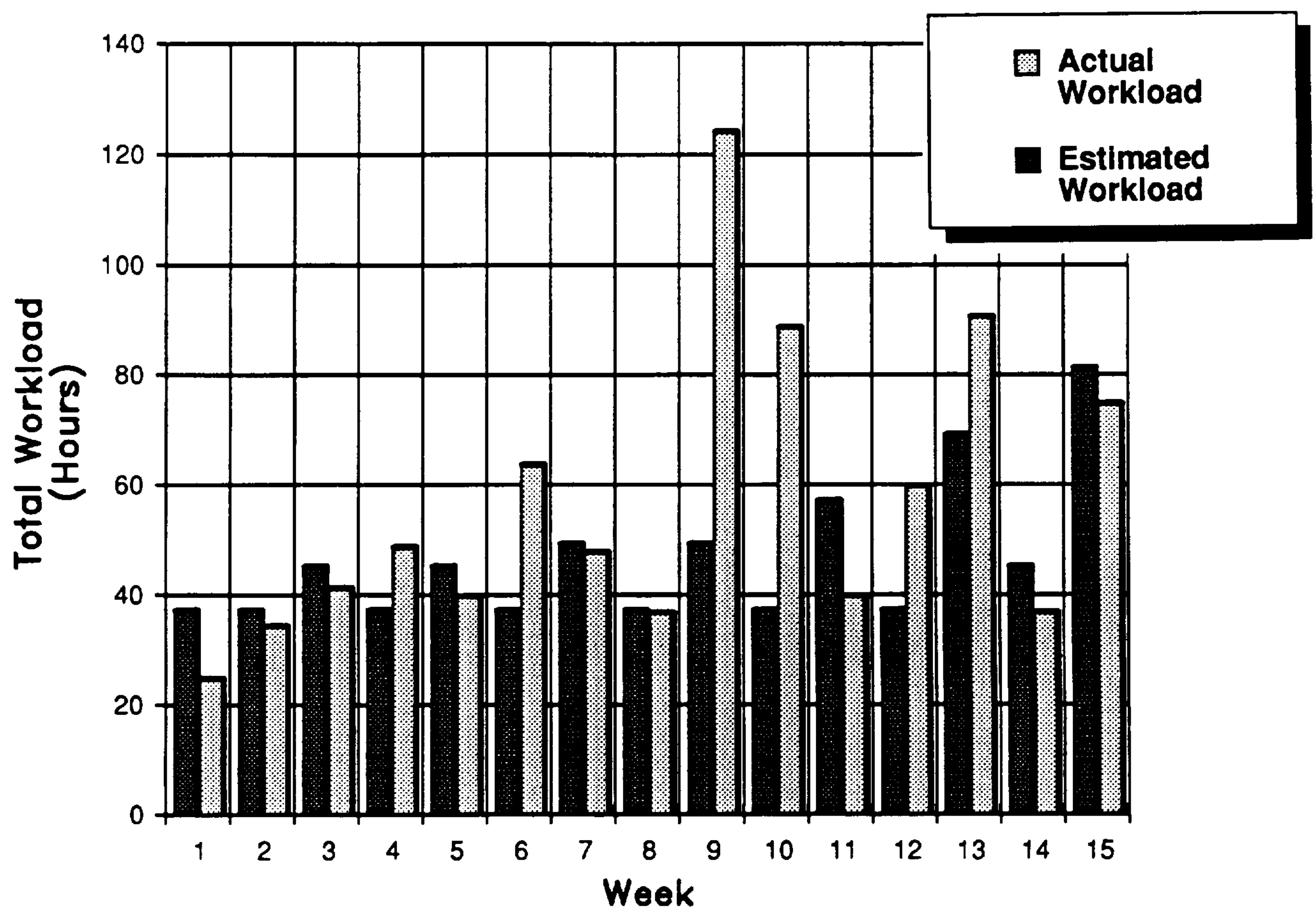


Figure 29. Personnel Workload per Week

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Appendix A

ASPEC

TK! Solver SPS Sizing Model

------------------- VARIABLE SHEET -------------------

St	Input	Name	Output	Unit	Comment
		SysEff	0.193971		Total System Efficiency
		PowerIn	25.777049	GW	Solar Power Collected
		ArrayArea	18.453038	km^2	Required Array Area
		ArrayCost	51.554098	$ Billion	Estimated Cost of Solar Arrays
		ArrayMass	20347.941	tons	Array Mass
	0.41	CellEff			Solar Cell Efficiency
	0.83	TransEff			Transmission Efficiency
	0.95	PropEff			Propogation Efficiency
	0.75	GndCnvEff			Ground Conversion Efficiency
	0.80	MiscEff			Miscellaneous Efficiency
	2.00	CostperW		$/W	Solar Cell Cost per Watt Generated
	5.0	PowerOut		GW	Ground Station Power Output
	1396.9	G_{sn}		W/m^2	Average Normal Solar Irradiation
	1.0	MassperArea		kg/m^2	Array Mass per unit Area

------------------- RULE SHEET -------------------

S	Rule
	PowerOut = SysEff * PowerIn
	ArrayArea = PowerIn / G_{sn}
	SysEff = CellEff * TransEff * PropEff * GndCnvEff * MiscEff
	ArrayCost = PowerIn * CostperW
	ArrayMass = ArrayArea * MassperArea

Appendix B

ASPEC
Consultant Services

Consultant	Affiliation	Week 1	Week 3	Week 4	Week 5	Week 6	Week 13	Personal Totals	Cost
Dr. John Lundberg	*Univ. of Texas at Austin, Dept. of Aerospace Engineering & Engineering Mechanics*	0.5						0.5	$37.50
Mr. Darrell Monroe	*Univ. of Texas at Austin, Dept. of Aerospace Engineering & Engineering Mechanics*		0.5					0.5	$37.50
Mr. Lewis Fraas	*Boeing High Technology Center*			0.5		2.5		3.0	$225.00
Mrs. Sandra L. Cohens	*Astro Power Division, Astrosystems Inc.*			0.5				0.5	$37.50
Dr. Gary Vliet	*Univ. of Texas at Austin, Dept. of Mechanical Engineering*				1.5			1.5	$112.50
Mr. Kurt Hoover	*Univ. of Texas at Austin, Dept. of Aerospace Engineering & Engineering Mechanics*				1.0			1.0	$75.00
Mr. Jim Gonzales	*Hercules Inc.*				0.5			0.5	$37.50
Mr. Dave Coarsemeyer	*Univ. of Texas at Austin, Dept. of Aerospace Engineering & Engineering Mechanics*						0.5	0.5	$37.50
	Totals:	0.5	0.5	1.0	3.0	2.5	0.5	8.0	$600.00

Appendix C

ASPEC
SPS Project Manhours

Employee Name	Week 1	Week 2	Week 3	Week 4	Week 5	Personal Totals	Salary
Mark Garrard	2	7	4	7	6	26	$650.00
Mike Timmons	9	6	8	4	6.5	33.5	$737.00
Clara V. Enriquez	2	4.5	1	6	4.5	18	$360.00
Victor Ugaz	0	5	8	12	3	28	$560.00
Ray Kokaly	9	6	8	4	5	32	$640.00
Brian Rogers	1	2	2.5	6	3	14.5	$290.00
Saumya Nandi	1	2	4	4	4	15	$225.00
Rommel Mercado	1	1	4	4	6	16	$240.00
Weekly Totals:	25	33.5	39.5	47	38	183	$3,702.00
Employee Name	**Week 6**	**Week 7**	**Week 8**	**Week 9**	**Week 10**	**Personal Totals**	**Salary**
Mark Garrard	8	7	9	10	15	49	$1,225.00
Mike Timmons	6	8	2	25	15	56	$1,232.00
Clara V. Enriquez	9	3	5	11	8	36	$720.00
Victor Ugaz	10	5	8	18	6	47	$940.00
Ray Kokaly	9	9	2	16	15	51	$1,020.00
Brian Rogers	3	3	2	2.5	6.5	17	$340.00
Saumya Nandi	8	7	3	24	10	52	$780.00
Rommel Mercado	9	4	4	17	7	41	$615.00
Weekly Totals:	62	46	35	123.5	82.5	349	$6,872.00
Employee Name	**Week 11**	**Week 12**	**Week 13**	**Week 14**	**Week 15**	**Personal Totals**	**Salary**
Mark Garrard	6	8	12	7	8	41	$1,025.00
Mike Timmons	9	9	17	3	8	46	$1,012.00
Clara V. Enriquez	3	5	9	5	4	26	$520.00
Victor Ugaz	4	8	7	8	5	32	$640.00
Ray Kokaly	9	9	17	3	8	46	$920.00
Brian Rogers	1	9	7	1	1	19	$380.00
Saumya Nandi	5	8	12	6	8	39	$585.00
Rommel Mercado	3	4	10	4	4	25	$375.00
Weekly Totals:	40	60	91	37	46	274	$5,457.00
					Project Totals:	806	$16,031.00

Appendix D

ASPEC
Project Supply Cost

Item	Price/Unit	Units	Estimated Cost	CDR Cost	Proposal Cost	UH Cost	PDR1 Cost	PDR2 Cost	NASA Cost	Total Cost
Copies / Laser Prints	$0.08	page	$160.00	$3.20	$6.72	$1.60	$26.88	$22.40	$11.52	$72.32
Transparencies	$0.50	page	$50.00	$12.50	$0.00	$10.00	$20.00	$10.00	$1.50	$54.00
Report Bindings	$2.00	report	$18.00	$0.00	$2.00	$0.00	$4.00	$2.00	$0.00	$8.00
Mainframe	$100.00	CPU-hr	$2,000.00	$0.00	$0.00	$50.00	$75.00	$250.00	$25.00	$400.00
Fax Copies	$2.00	page	$50.00	$0.00	$0.00	$12.00	$0.00	$0.00	$0.00	$12.00
Long Distance Calls	$15.00	hr	$45.00	$15.00	$0.00	$37.50	$0.00	$3.75	$0.00	$56.25
		Total =	$2,323.00	$30.70	$8.72	$111.10	$125.88	$288.15	$38.02	$602.57

Appendix E

ASPEC
Constant Thrust Transfer Approximation

The transfer from LEO to GEO is accomplished under a continuous tangential thrusting SSAP. The low thrust enables analytic solution to be obtained for LEO to escape condition with the aid of a few assumptions [20: 417-418] However, we are interested in a LEO to GEO transfer so an approximation method is used to size the thrusters. This approximation is accomplished by comparing results from previous studies to their escape times as calculated by the program on the following page. The ratio between the escape time and the published time form the percentage of time it takes to go to GEO instead of escaping. The desired time of flight is 150 days and the thrust of the engines is modified to reach so that the desired TOF is met. The TK Solver program listed on the following page uses the equations below to calculate the thruster rating for four thrusters on each SSAP.

$$s_{esc} = \frac{v_o^2}{2a}\left[1 - \frac{1}{v_o}\left(20a^2 r_o^2\right)^{.25}\right]$$

$$r_{esc} = \frac{r_o v_o}{\left(20a^2 r_o^2\right)^{.25}}$$

$$t_{esc} = \frac{v_o}{a}\left[1 - \left(\frac{20a^2 r_o^2}{v_o^4}\right)^{.125}\right]$$

$$N_{esc} = \frac{v_o^2}{8\pi a r_o}\left(1 - \frac{\sqrt{20}\,a r_o}{v_o^2}\right)$$